SUBCOURSE
MM5005

EDITION
8

U.S. ARMY AVIATION CENTER

RADAR TRANSMITTER

THIS SUBCOURSE HAS BEEN REVIEWED FOR OPERATIONS SECURITY.

THE ARMY INSTITUTE FOR PROFESSIONAL DEVELOPMENT
ARMY CORRESPONDENCE COURSE PROGRAM

AIPD

READINESS/
PROFESSIONALISM
THRU
GROWTH

US ARMY AIR TRAFFIC CONTROL SYSTEMS/SUBSYSTEMS EQUIPMENT REPAIR
MOS 93D SKILL LEVELS 1 AND 2

PLEASE NOTE

Proponency for this subcourse has changed
from Aviation (AV) to Missile & Munitions (MM).

RADAR TRANSMITTERS
(Development Date: 1 November 1987)

SUBCOURSE NUMBER: AV 5005

US ARMY AVIATION CENTER
FORT RUCKER, ALABAMA 36362-5000

10 CREDIT HOURS

GENERAL

The Radar Transmitters subcourse is part of the Air Traffic Control System/Subsystems Equipment Repair Course, MOS 93D. This subcourse is designed to teach the knowledge and skills necessary to troubleshoot and repair radar transmitters. This subcourse is presented in four lessons consisting of 14 learning events, each lesson corresponding to a terminal objective as indicated below.

Lesson 1
TRANSMISSION LINES

TASK

Identify transmission lines used with radar systems, describe the composition and electrical characteristics of real transmission lines on schematic diagrams, and determine time delays in artificial transmission lines.

CONDITIONS

(Performance-Oriented) Given this subcourse, pencil, and paper.

Whenever pronouns or other references denoting gender appear in this document, they are written to refer to either male or female unless otherwise indicated.

STANDARD

(Performance-Oriented) Demonstrated competency of task skills and knowledge by correctly responding to 75 percent of the multiple-choice test covering radar transmitters.

(This objective supports SM Task Numbers 011-151-0003, Repair Radar Set AN/TPN-18; 011-151-0104, Repair Radar Set AN/TPN-18A; 011-151-0128, Repair Interrogator Set AN/TPX-44; 011-151-4002, Repair Radar Set AN/FPN-40; 011-151-4049, Repair Interrogator Set AN/TPX-41.)

Lesson 2
HIGH-LEVEL MODULATION

TASK

Describe the functions performed by the components in a high-level modulator circuit, differentiate between conventional and hydrogen thyratron circuit operations, determine the width and amplitude of the pulse applied to the magnetron in a high-level modulator circuit, and differentiate between conventional transformers and pulse transformers.

CONDITION

(Performance-Oriented) Given this subcourse, pencil, and paper.

STANDARD

(Performance-Oriented) Demonstrate competency of task skills and knowledge by correctly responding to 75 percent of the multiple-choice test covering radar transmitters.

(This objective supports SM Task Numbers 011-151-0003, Repair Radar Set AN/TPN-18; 011-151-0104, Repair Radar Set AN/TPN-18A; 011-151-0128, Repair Interrogator Set AN/TPX-44; 011-151-4002, Repair Radar Set AN/FPN-40; 011-151-4049, Repair Interrogator Set AN/TPX-41.)

Lesson 3
RESONANT CAVITIES AND MAGNETRONS

TASK

Describe resonant cavities and magnetron operations, recognize coupling and tuning techniques employed with resonant cavities and magnetrons, identify different types of magnetrons and describe their modes of operation.

CONDITION

(Performance-Oriented) Given this subcourse, pencil, and paper.

STANDARD

(Performance-Oriented) Demonstrate competency of task skills and knowledge by correctly responding to 75 percent of the multiple-choice test covering radar transmitters.

(This objective supports SM Task Numbers 011-151-0003, Repair Radar Set AN/TPN-18; 011-151-0104, Repair Radar Set AN/TPN-18A; 011-151-0128, Repair Interrogator Set AN/TPX-44; 011-151-4002, Repair Radar Set AN/FPN-40; 011-151-4049, Repair Interrogator Set AN/TPX-41.)

Lesson 4
ANTENNAS AND WAVEGUIDES

TASK

Describe how RF energy is transferred through waveguides, recognize the various waveguide tuning and coupling devices, identify the various antennas and reflectors used in radar systems, and differentiate between front and rear antenna feed systems.

CONDITION

(Performance-Oriented) Given this subcourse, pencil, and paper.

STANDARD

(Performance-Oriented) Demonstrated competency of task skills and knowledge by correctly responding to 75 percent of the multiple-choice test covering radar transmitters.

(This objective supports SM Task Numbers 011-151-0003, Repair Radar Set AN/TPN-18; 011-151-0104, Repair Radar Set AN/TPN-18A; 011-151-0128, Repair Interrogator Set AN/TPX-44; 011-151-4002, Repair Radar Set AN/FPN-40; 011-151-4049, Repair Interrogator Set AN/TPX-41.)

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***** IMPORTANT NOTICE *****

THE PASSING SCORE FOR ALL ACCP MATERIAL IS NOW 70%.

PLEASE DISREGARD ALL REFERENCES TO THE 75% REQUIREMENT.

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ADMINISTRATIVE INSTRUCTIONS
(PERFORMANCE-ORIENTED)

SUBCOURSE CONTENT

This subcourse contains four lessons designed to acquaint you with radar transmitters. You will study and analyze transmitter waveforms, circuits that generate the transmitter pulse, and the antenna that sends the RF energy into space.

Supplementary Requirements. None

Materials Needed. You will need a Number 2 pencil and paper to complete this subcourse. No other materials are required.

Supervisory Assistance. There are no supervisory requirements for completion of this subcourse.

References. No supplementary references are needed for this subcourse.

Subcourse Prerequisite. MOS Holder

GRADING AND CERTIFICATION INSTRUCTIONS
(PERFORMANCE-ORIENTED)

INSTRUCTIONS TO STUDENT

1. This subcourse has a posttest that is a performance-oriented multiple-choice test covering four lessons. After you have studied each lesson, solve the practice exercises. Reread the lesson for any portion you miss. When you have studied the entire subcourse, and solved the practice exercises, you will be ready to take the examination. You may refer to the lesson text and references when solving the examination. Follow the specific instructions that precede the examination. You must score a minimum of 75 percent on this test to meet the objectives of the subcourse. Answer all questions on the enclosed ACCP examination response sheet. After completing the posttest, place the answer sheet in the self-addressed envelope provided and mail it to the Institute for Professional Development (IPD) for scoring. IPD will send you a copy of your score. A student inquiry sheet is provided. We urge you to use it if you have a comment or question about the subcourse. This subcourse, at time of printing, conforms as closely as possible to US Army Aviation Center and Department of the Army doctrine. Therefore, you should base your solutions on the subcourse text and not on unit or individual experience.

2. 10 credit hours will be awarded for the successful completion of this subcourse.

3. You are urged to finish this subcourse without delay; however, there is no specific limitation on the time you may spend on any lesson or the examination.

INTRODUCTION

The transmitter is the subsystem of the radar that produces the short duration, high-power RF pulses of energy that are focused and radiated into space by the antenna. The history of the practical radar transmitter began in 1940 when Great Britain developed a successful cavity magnetron. This made it possible to generate substantial amounts of power at microwave frequencies. During that year, samples of the cavity magnetron were brought to the Radiation Laboratory at Massachusetts Institute of Technology, where research and development work was started in the microwave field. The term RADAR is an acronym from the expression Radio Detection and Ranging. The heart of the radar system is the transmitter. Two main types of transmitters are now in common use. The first is the keyed-oscillator type. In this transmitter, one stage or tube, usually a magnetron, produces the RF pulse. The oscillator tube is keyed by a high-power DC pulse of energy generated by a separate unit called a modulator. The second type of transmitter consists of a power-amplifier chain. This transmitter system begins with an RF pulse of very low power. This low-level pulse is then amplified by a series of power amplifiers to the high level of power desired in a transmitter pulse. In most power-amplifier transmitters, each of the power-amplifier stages is pulse modulated in a manner similar to the oscillator in the keyed-oscillator type. This subcourse is designed to familiarize you with the radar transmitters and systems associated with RF propagation.

LESSON ONE

TRANSMISSION LINES

TASK

Identify transmission lines used with radar systems, describe the composition and electrical characteristics of real transmission lines on schematic diagrams, and determine time delays in artificial transmission lines.

CONDITIONS

(Performance-Oriented) Given this subcourse, pencil, and paper.

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REFERENCES

FM 11-63

Learning Event 1:
RF TRANSMISSION LINES

1. GENERAL.

a. RF transmission lines are used to transfer or guide RF energy from one place to another with a minimum loss of power. Transmission lines serve as the connecting link between a source of power and the load which uses the power. Transmission lines in radio, television, and radar systems guide the RF signal from the transmitter to the transmitting antenna and from the receiving antenna to the receiver.

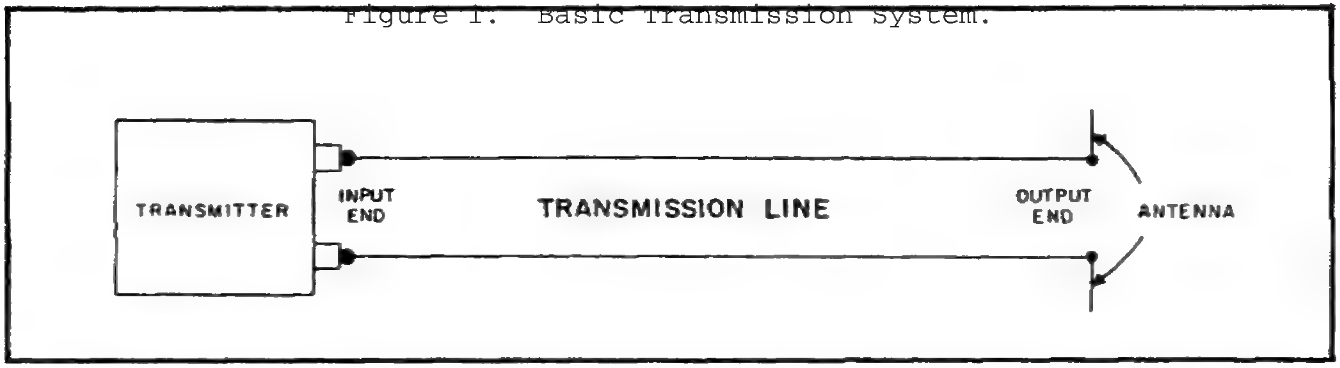
b. RF transmission lines are like the wires that carry electric power and telephone messages to your home. In fact, all transmission lines contain the same basic properties of resistance, inductance, and capacitance. In this respect a transmission line is similar to ordinary circuits. However, the basic low-frequency transmission line made of wires is not an efficient carrier of RF energy because power losses increase as the operating frequency increases. RF transmission lines therefore, must be carefully designed to overcome the limitations of the basic low-frequency line. Regardless of the operating frequency, all transmission lines should have the smallest possible losses in order to transfer the maximum power to the load.

c. In this lesson, you will study the properties and characteristics of transmission lines used to guide RF energy from source to load. Also, you will learn how transmission lines are used as circuit components. For example, you will learn how a section of transmission line is used as an impedance-matching transformer and how a small length of line is used as the tank circuit in an UHF oscillator. These applications are especially important in the fields of radar and microwave.

2. First, a few terms.

a. Figure 1 shows a transmission line used to couple RF energy from a transmitter to the antenna of a communications system. The transmission line has an INPUT END and an OUTPUT END. The transmitter is coupled to the input end, also called the generator end or source. The antenna is coupled to the output end, also called the load end or sink.

Figure 1. Basic Transmission System.



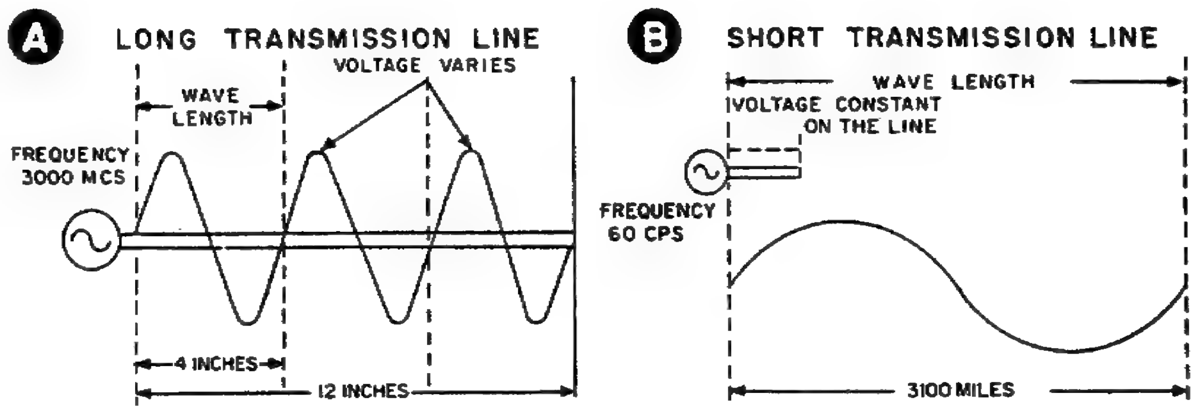
b. A transmission line can be called long or short. A transmission line is long when its length is long compared to the wavelength of the RF signal place on it by the source. It is short when its length is short compared to the wavelength. The long-short concept is an important one for you to understand, for it explains why a piece of wire can act as a tank circuit at ultra-high frequencies.

3. When is a transmission line long?

A transmission line is long when its length is long compared to the wavelength of the frequency used. It is not just the physical length alone, but rather the ratio of physical length to the wavelength. For example, look at Part A of Figure 2 which shows a generator coupled to a transmission line. The length of the transmission line is 12 inches. Now, 12 inches of transmission line doesn't seem long when you compare its length to that of the room you're in. But when you compare this 1 foot of transmission line to the wavelength of 3000 megahertz, you find that the line isn't so

short after all. You can fit three complete wavelengths on a foot of transmission line because the wavelength of 3000 megahertz is approximately 4 inches. Notice that the voltage changes along the line because the transmission line is long compared to the 3000 megahertz wavelength.

Figure 2. Transmission Lines can be LONG or SHORT.



4. When is a transmission line short?

A transmission line is called short when its length is short compared to the wavelength of the source frequency. Let's use our 1-foot transmission line again. This time let's couple the line to a source whose frequency is 60 hertz, as shown in Part B of Figure 2. The wavelength of 60 hertz is approximately 3,100 miles. Notice that the voltage is constant because the transmission line is so short.

5. We are concerned with long lines.

In this learning event we will concern ourselves only with long lines. By long, of course, we are referring to electrical length of the transmission line, not its physical length. Where is the dividing point between long and short? No definite value can be given because a line does not change suddenly from short to long. As a rough approximation, consider a line shorter than one sixteenth wavelength as a short line. Keep in mind, however, that we mean electrical length when we say a line is short or long. Actually, a transmission line only a few inches in length may be a long line at ultra-high frequencies.

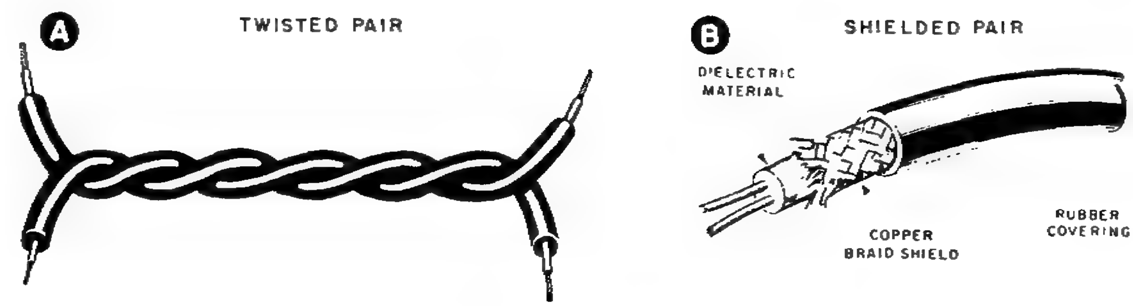
6. Types of transmission lines.

Before we go further into transmission line principles, let's see what types of transmission lines you're likely to meet in your work. There are many types of transmission lines in use today. Each type has its own particular advantages. The choice of transmission line for any specific installation depends on the amount of power to be transmitted, the frequency of operation, and the length of line needed. Only the more common types of transmission lines are described here.

7. The twisted pair.

a. This type of line, shown in Part A of Figure 3, consists of two unshielded insulated conductors twisted together. Twisting the wires holds the lines together and helps to reduce radiation losses. Radiation losses occur at higher frequencies. At RF frequencies, the transmission line acts like an antenna, radiating the RF energy into space. Thus, most of the signal is lost before it gets to the antenna.

Figure 3. The Twisted Pair and Shielded Pair.



b. In radar installations, the twisted pair is used for power transmission over short distances. It is not used at very high frequencies because of excessive losses occurring in the rubber insulation. This type of loss is known as a dielectric loss. The twisted pair cannot be used above 15 megahertz because of excessive dielectric and radiation losses. The only advantages of the twisted pair type of line are its simplicity, ease of installation, and low cost. The practical range of characteristic impedance is from approximately 70 to 150 ohms. Characteristic impedance will be explained in detail later.

8. The shielded pair.

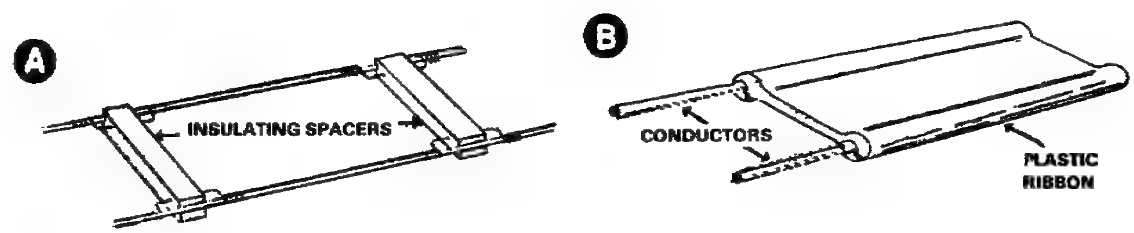
The shielded pair type transmission line shown in Part B of Figure 3 is used mainly for power transmission of frequencies up to 30 megahertz. Above 30 megahertz, excessive losses occur in the insulating material. The shielded pair has low radiation losses because the two conductors are completely surrounded by a copperbraid which acts as a shield. A rubber covering surrounds the outside copper shield. This type of line can be run close to metal surfaces without serious losses. The shielded pair is available in characteristic impedances of approximately 40 to 150 ohms.

9. The parallel pair.

a. There are two parallel pair types: the open two-wire line shown in Part A of Figure 4; and the insulated two-wire line, commonly known as ribbon parallel line, shown in Part B of Figure 4. The open two-wire line uses air as the dielectric. The two wires are kept at the same distance apart for the entire length by insulating bars called spacers or spreaders. The spacing between conductors may vary from 2 to 6 inches, depending on the voltage between the two wires and the frequency of the applied voltage. Closer spacing is preferable at higher frequencies to reduce radiation losses.

b. The insulated two-wire line shown in Part B of Figure 4 uses a solid, flexible dielectric such as polyethylene. This type is used to connect a television receiving antenna to a TV set. Its low cost, low loss, and simplicity make it ideal for such installations.

Figure 4. Two-Wire Parallel Conductor Transmission Line.



c. In general, parallel conductor lines have advantages of low cost, and high efficiency, because of their low losses. Also, they are easy to construct and install. Characteristic impedances range from approximately 75 to 500 ohms. The parallel conductor line can be used for frequencies up to 200 megahertz. Above 200 megahertz, high radiation losses occur, particularly near metal surfaces.

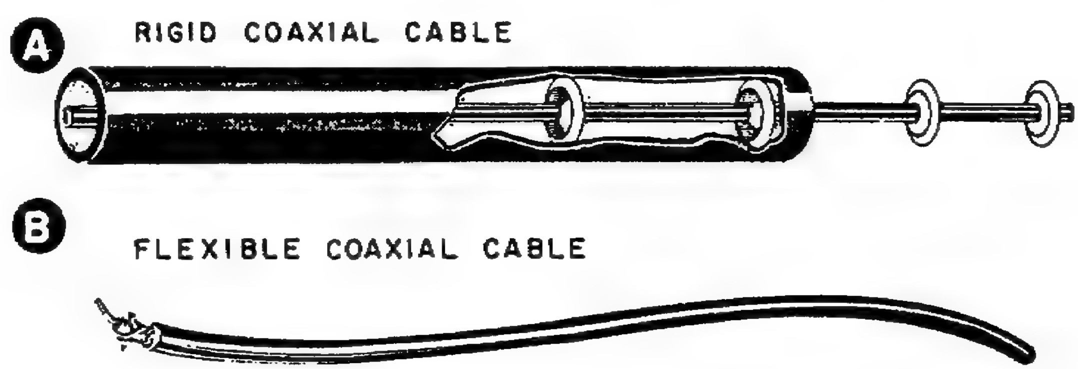
10. The coaxial line.

a. The coaxial line is used widely as a transmission line at frequencies up to 3000 megahertz. It consists of a hollow copper tube through which another copper tube is run coaxially (having the same axis) with the outer tube. See Part A of Figure 5. Current flows along the outer surface of the center conductor and along the inner surface of the outer conductor. The outer conductor may be grounded since current flows only on its inner surface.

b. The inner copper tube is insulated from the outer conductor by spacers made of pyrex, polystyrene, or some similar insulating material. The conducting surfaces are often silverplated to reduce losses due to resistance. Also, the coaxial line is usually pressurized to keep out moisture. Moisture inside the cable causes the RF energy to arc over, resulting in a power loss.

c. The coaxial transmission line may be made flexible as shown in Part B of Figure 5. The space between the wire inner conductor and outer conductor is filled with a flexible plastic insulating material called polyethylene. The outer conductor is made of copper braid. The flexible coaxial line has somewhat higher losses than the rigid line because of the polyethylene.

Figure 5. Types of Coaxial Transmission Line.



d. Coaxial lines are superior to two-wire parallel lines because of the perfect shielding provided by the outer conductor. Shielding not only prevents radiation but also prevents noise pickup from external sources. This is one reason why coaxial lines are widely used for television lead-ins in noisy locations.

e. The chief disadvantage of coaxial lines at the higher frequencies is the loss of power due to skin effect. Skin effect is the result of current flowing on the outside of conductors. The power loss is due to the increased resistance

to current flow. Coaxial lines are more difficult to construct than other types of transmission lines. As a result, they are more expensive. The characteristic impedance of coaxial lines ranges from approximately 10 to 150 ohms. The diameter of the conductors determines the characteristic impedance.

11. Review of transmission line types.

The following chart summarizes the main points to remember about the different transmission lines. Notice that the waveguide appears at the bottom of the chart. The waveguide is a special type of transmission line used at frequencies above 3000 megahertz. Waveguides are discussed in lesson four.

Figure 6. Types of Transmission Lines.

NAME	UPPER LIMIT	GREATEST LOSS DUE TO	CHAR IMP	APPLICATIONS
1. TWISTED pair	15 MHz	Dielectric	70-150 ohms	Power transmission over short distances.
2. SHIELDED pair	30 MHz	Dielectric	40-150 ohms	Power transmission.
3. PARALLEL pair	200 MHz	Radiation	75-500 ohms	Antenna feed wavelength measurements.
4. COAXIAL line	3000 MHz	Skin effect	10-150 ohms	Antenna feed, circuit components.
5. WAVE-GUIDES	None	None	0-465 ohms	Antenna feed, circuit components.

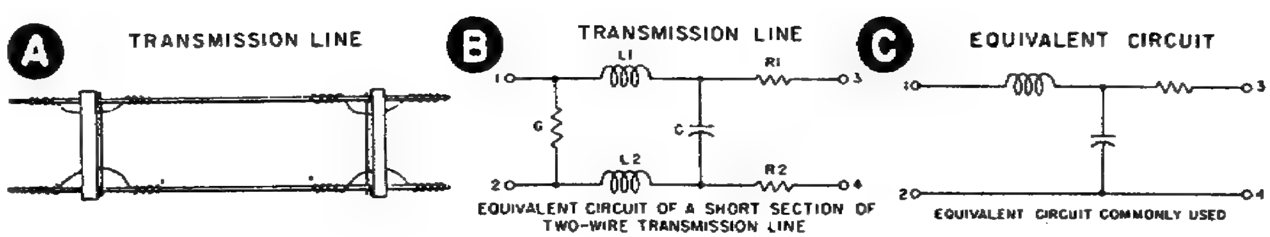
12. A transmission line is similar to ordinary circuits.

a. To begin our detailed study of transmission lines, first consider what they are: Wires! When you study circuits such as multivibrators, blocking oscillators, and other circuits, you use a schematic. You analyze these circuits in terms of current and voltage. The use and understanding of symbols in the schematic to represent resistors, capacitors, inductors, and vacuum tubes makes the circuit more logical and easier to understand. In transmission lines, all we have are wires. This means that we will have to consider transmission lines in some manner that will make them more logical and easier to understand.

b. One means by which we can study transmission lines is to use an equivalent circuit. This is easy to do because RF transmission lines are similar to ordinary circuits in all respects except for their length. Ordinary circuits contain "lumped properties;" that is, actual physical components. RF transmission lines also have resistance, capacitance, and inductance. But these components appear in the form of "distributed properties." When you understand the equivalent circuit of a simple type of transmission line, such as a parallel pair, then you will have a clearer understanding of other types of lines.

c. First, consider what a parallel pair transmission line is. It consists of two wires of constant diameter, evenly spaced, and running parallel. By representing this line as a simple equivalent circuits, we can analyze it more easily. Figure 7 shows a parallel pair transmission line and its equivalent circuit. Notice in Part B of Figure 7 that the transmission line has resistance and inductance in series with the line. There is capacitance between the conductors regardless of the spacing between the wires. Also, there is a high-resistance (G), low-conductance leakage path between the two conductors because no material is a perfect insulator. Keep in mind that the line does not contain actual physical resistors, capacitors, and inductors. Instead, the properties are distributed throughout the line. Part C of Figure 7 shows the equivalent circuit commonly used.

Figure 7. The Electrical Equivalent of a Transmission Line.



d. As you know, all AC circuits have an opposition to the flow of alternating current. This opposition is called impedance. A transmission line also has impedance.

13. A transmission line has a characteristic impedance.

a. Impedance is the combined opposition of resistance, capacitive reactance, and inductive reactance. In a transmission line, the impedance to RF is caused by the distributed properties of resistance, capacitance, and inductance. This impedance is called characteristic impedance. The symbol for characteristic impedance is Zo. It is measured in ohms.

b. The characteristic impedance of a transmission line is determined by the following:

(1) Size of the wire use.
(2) Spacing between the wires.
(3) Insulation used to separate the wires.

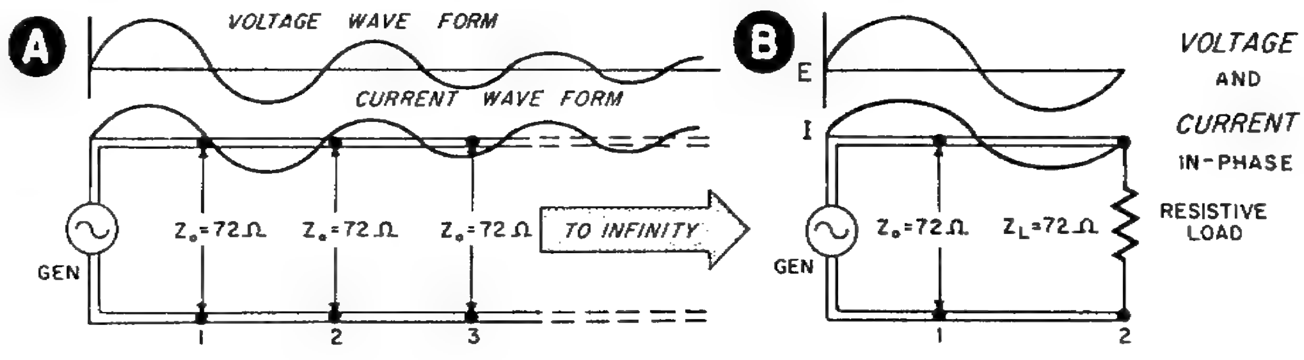
c. The characteristic impedance is not affected by the length of the line.

14. Why is characteristic impedance important?

a. Imagine that you have a generator coupled to a transmission line that is infinite in length as in Part A of Figure 8. That is, the transmission line has no end--it just goes on and on to infinity. Now, put an ammeter at the input end and apply a voltage to the line. The ammeter, surprisingly enough, indicates that current is flowing in the line. You're probably asking, "How can current flow when we don't have a complete circuit?" But we do have a complete circuit--through the distributed properties of the line. The amount of current that flows on the line depends upon the applied voltage and the distributed properties of resistance, capacitance, and inductance. The impedance at the input, Zo, then, is equal to the applied voltage divided by the line current.

b. The RF energy, and by this we mean current and voltage, travels down the infinite line in phase. The amplitude drops off somewhat because of the resistance of the line. The RF signal never reaches the load at the far end, so none of it ever comes back. The input impedance that the energy meets at point 2 in Part A of Figure 8 is the same as the input impedance at point 1. This is so because the ratio of applied voltage to line current remains constant at any point on an infinite line. The RF energy goes past point 2 because the impedance ahead is exactly like the impedance it has just passed through. The same thing holds for point 3. Since none of the energy ever reaches the end of the line, then the load impedance has no effect on the input impedance of the line.

Figure 8. The Infinitely Long Line.



15. A properly terminated line acts like an infinite line.

a. By now you are probably wondering why all this discussion regarding an infinite line, when no such line exists. You are right, but we do have a line that acts like an infinite line.

b. Suppose we remove a section from the infinite line between points 1 and 2. How does this affect the characteristic impedance of the line? It doesn't. The length of the line from point 2 on is still infinite. Now let's take this section of line and connect a resistive load equal to the characteristic impedance at point 2. See B of Figure 8. Assume that Zo equals 72 ohms. As far as the input is concerned, the impedance at point 2 is still equal to 72 ohms (Zo), just as if the line had extended out to infinity. By terminating the line in a resistive load equal to Zo (72 ohms) of the line, we have made the real line appear infinite. The voltage and current go down the line in phase. And what is more important, all the energy placed on the line is absorbed by the load. We can say, then, that a transmission line presents its characteristic impedance at its input when the line is terminated by a load equal to the line's characteristic impedance. Maximum power transfer occurs. That is why the characteristic impedance of a line is so important.

16. The main points so far.

a. Terminating a line with a resistive load equal to the characteristic impedance of the line makes the line act like an infinite line. The terminated line then behaves as follows:

(1) The input impedance is equal to Zo (the characteristic impedance) and is resistive.

(2) Voltage and current travel down the line in phase.

(3) The ratio of voltage to current at any point on the line is constant and equals Zo.

(4) There is maximum transfer of power from source to load.

b. Less power is lost when the transmission line is fitted or matched to the load. What happens when the transmission line does not match the impedance of the load? Reflections occur when there is an impedance mismatch between the transmission line and the load. Reflections cause a loss in power known as reflection loss.

17. Reflections occur when there is a sudden change in impedance.

a. Let's take the statement apart and see what it really means. Suppose you're in a room and you call your buddy outside. The sound of your voice reaches him, but some of the power of your voice is lost before it gets to him. The loss takes place at the walls of the room. We can call this loss of sound, reflection loss.

b. The sound of your voice does all right traveling through the air until it hits the wall. Some of the sound continues through the wall to the outside. Another portion of the sound is reflected or bounced back to you. The reflection is called an echo. How much of the sound is reflected depends on how hard the wall is. A hard, solid wall causes a lot of reflection, because the sound can't penetrate the wall as well as it can penetrate the air. Part of the sound can't get through the wall at all. The reflection takes place right at the point where the conductors change, from air to wood. The reflection loss of sound, then, is caused by a change or mismatch in the impedance of the conductors. The loss occurs right at the point where the mismatch is located, in this case, the wall.

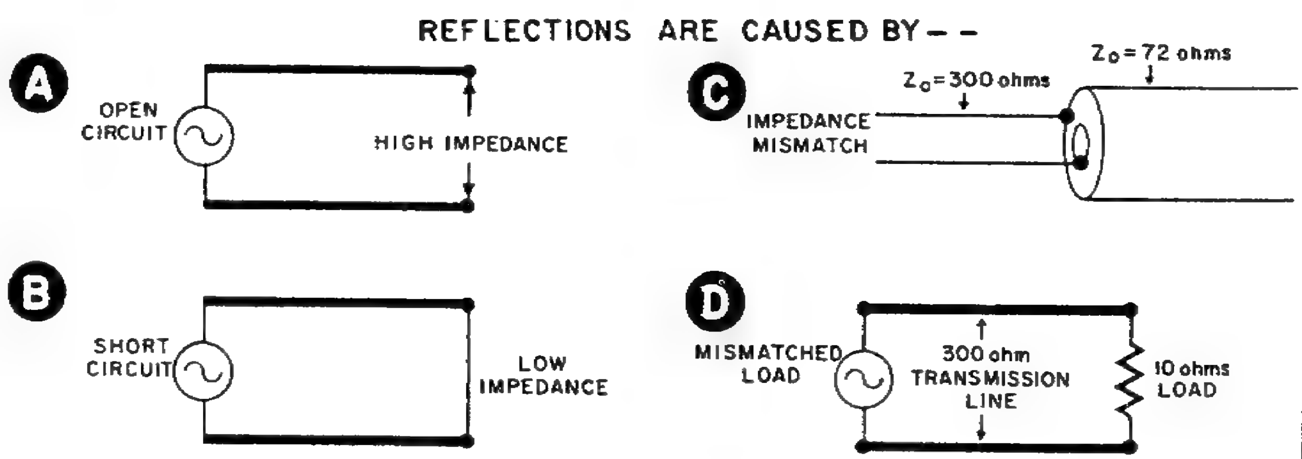
18. The same thing happens in RF transmission lines.

a. A reflection occurs when the RF energy meets a sudden change in impedance. When the RF energy reaches the point where the mismatch occurs, part of the wave is reflected back to the source. This means less energy is available for the load. This is reflection loss.

b. What is a sudden change in impedance? Well, for one thing, an open circuit is a sudden impedance change. The RF energy does all right traveling along the transmission line because the impedance is uniform throughout the line. Then all at once the RF energy hits the open circuit which has an infinite impedance. See Part A of Figure 9. The change in impedance is so sudden and so large that all of the RF energy is reflected.

c. A short circuit is a sudden impedance change too. The impedance of a short circuit is practically zero. So, when the RF energy hits the short (Part B of Figure 9), all of the energy is reflected. No energy gets to the load at all.

Figure 9. Reflections are Due to Impedance Mismatches.



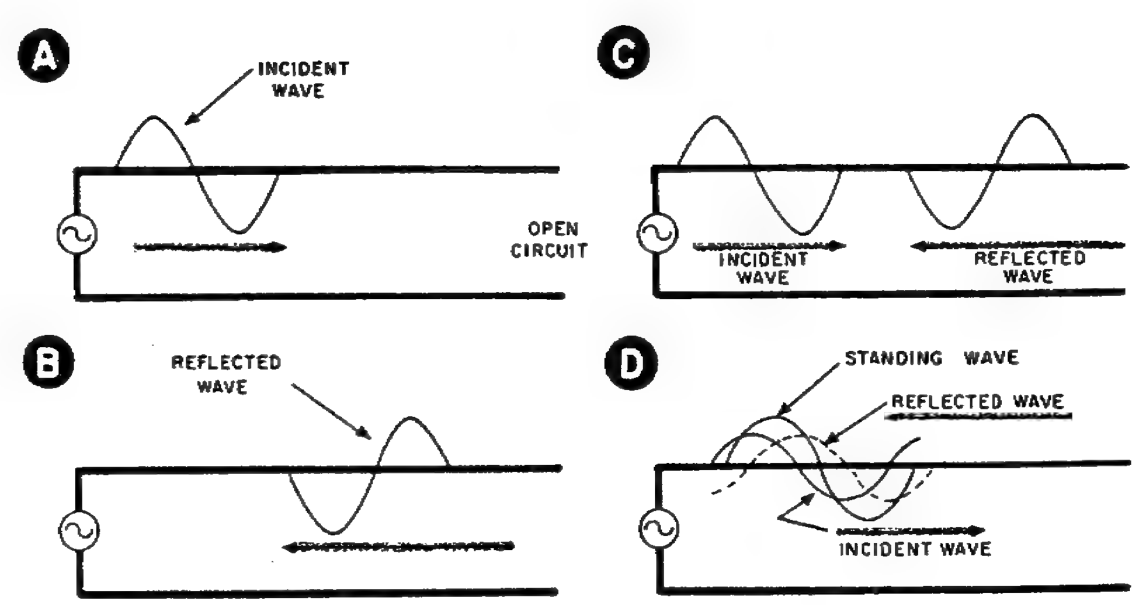
d. The same thing happens if we connect one transmission line to another having a different characteristic impedance (Part C of Figure 9). Also, if a transmission line is connected to any load other than a resistive load that is equal to the characteristic impedance of the line, reflections occur as in Part D of Figure 9. However, only a part of the RF energy is reflected. The amount reflected depends on how much of an impedance mismatch exists. The closer the impedances are matched, the less the amount of energy reflected.

19. Reflections cause standing waves.

a. When RF energy meets a sudden impedance change, all or part of the energy travels back to the source. Look at Part A of Figure 10 showing an RF generator coupled to a parallel-pair type transmission line. The end of the line is open and, therefore, presents a sudden change in impedance to the RF energy. The RF energy placed on the transmission line by the source is called the incident wave.

b. The incident wave of RF energy travels down the line in the form of voltage and current waves. When the RF energy reaches the open end of the line, the current wave drops to zero because it can go no further. The magnetic field that is always associated with the flow of current collapses, developing an induced voltage on the line. The induced voltage tries to keep current flowing in the same direction as before. But, there is no line extending to the right on which the current can flow. The only place for the current to go is back to the source. The energy traveling back to the source is called a reflected wave as shown in Part B of Figure 10.

Figure 10. Formation of Standing Waves.



20. There are two waves traveling on a transmission line.

a. So, now we have two waves traveling on the transmission line in opposite directions. One, the incident wave, is traveling from the source out to the open end of the line. The other, the reflected wave, is traveling back to the source from the open end of the line. This condition is shown in Part C of Figure 10. Notice that the phase of the reflected current wave is 180 degrees out of phase with the incident current wave.

b. Now, the reflected wave of the RF current travels away from the open end of the line. It meets the incident current waves coming from the generator. At every point on the line, these two waves combine to produce a resultant wave, called a standing wave. Part D of Figure 10 shows how the incident and reflected waves combine to produce a standing wave.

21. Standing waves are stationary.

a. Figure 10 shows that the standing wave is stationary, it does not move. As the incident wave and reflected wave move past each other, the standing wave changes only its amplitude. Let's see why this is so with the help of Figure 11.

(1) Part A of Figure 11 shows the incident wave and the reflected wave in phase. Adding the two current waves gives a resultant or standing wave of current equal to twice the amplitude of the traveling waves.

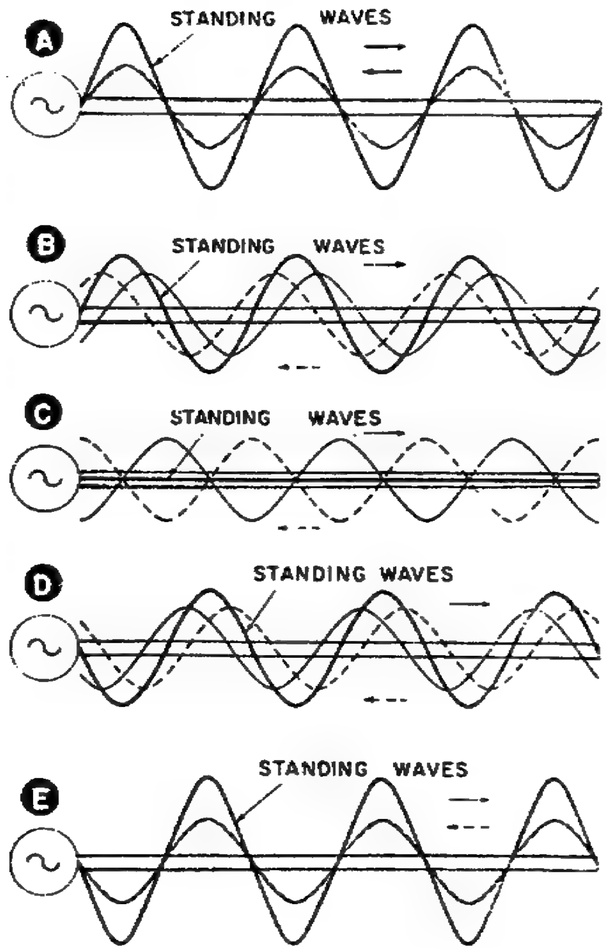
(2) Part B of Figure 11 shows a 90 degree phase difference between the incident and reflected current waves because they are moving away from each other. Notice that although the amplitude of the standing wave has decreased, the minimum and maximum points lie in the same place as they did in Part A of Figure 11.

(3) Part C of Figure 11 shows 180 degrees phase difference between the incident and reflected waves. The two waves cancel each other. There is no standing wave of current at this particular time.

(4) Part D of Figure 11 shows 270 degrees phase difference between the two traveling waves. Notice now that, although the minimum and maximum points are in the same position, the amplitude has reversed its direction.

(5) Part E of Figure 11 shows the two current waves in phase again. The resultant wave is equal in amplitude but 180 degrees out of phase with the standing wave shown in Part A of Figure 11.

Figure 11. Standing Waves Change in Amplitude But Do Not Move.



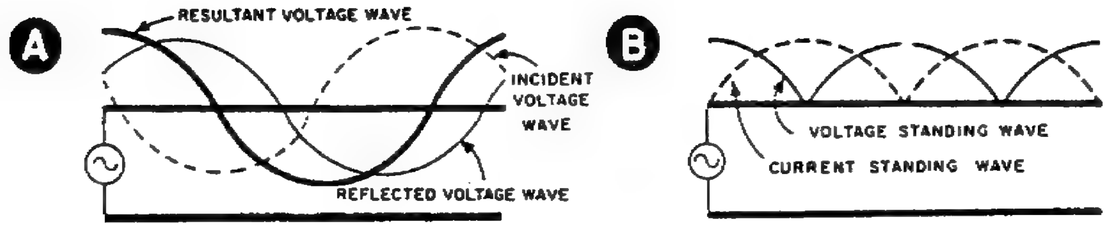
b. You see now that a standing wave results when the incident and reflected waves combine. Keep in mind, however, that there is only the resultant or standing wave on the line. Its amplitude keeps changing, but it remains in the same place.

22. There is also standing wave of voltage.

a. So far we have shown how a standing wave of current is formed on an open-end line. There is also a standing wave of voltage formed. The collapse of the magnetic field resulting from the stoppage of current at the open end of the line develops an induced voltage on the line. This new voltage wave cannot travel to the right in Part A of Figure 12 because there is no line there. So, it must travel back to the source as a reflected wave of voltage. The phase of this reflected voltage wave is the same as the incident voltage wave. The incident and reflected waves combine to produce a resultant standing wave of voltage.

b. Part B of Figure 12 shows both current and voltage standing waves on an open-end line. Notice that only one polarity is shown. The reason is that when you used an AC meter to determine current and voltage on a transmission line, it indicates amplitude but not polarity. All the readings are positive because of current rectification in the meter.

Figure 12. Standing Waves of Current and Voltage on an Open-End Line.



23. Review of standing waves on an open-end line.

a. Current is zero at the open end.

b. Current is reflected out of phase.

c. Voltage is maximum at the open end.

d. Voltage is reflected in phase.

e. Standing waves of current and voltage are 90 degrees out of phase.

24. Standing waves on a shorted line.

a. Now, suppose we place a bar across the ends of the open line, thus short-circuiting the transmission line as in Figure 13. The short circuit presents a sudden impedance change to the incident RF energy. The impedance change is so great that all of the RF energy is reflected back to the source. Again standing waves result when the incident and reflected waves combine.

b. Part A of Figure 13 shows that the current is maximum at the short circuit. As you know, this happens across any short circuit. The voltage, however, is practically zero at the short circuits (Part B of Figure 13). The current and voltage standing waves are 90 degrees out of phase (Part of Figure 13). The conditions existing on a shorted line are as follows:

(1) Voltage is zero at the short.

(2) Voltage is reflected out of phase.

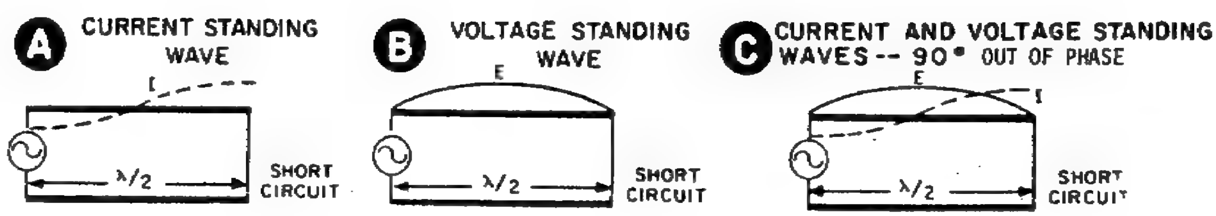
(3) Current is maximum at the shorted end.

(4) Current is reflected in phase.

(5) Standing waves of current and voltage are 90 degrees out of phase.

c. Notice that these conditions are exactly opposite to those existing on the open-end line (Figure 12).

Figure 13. Standing Waves on a Shorted Line.



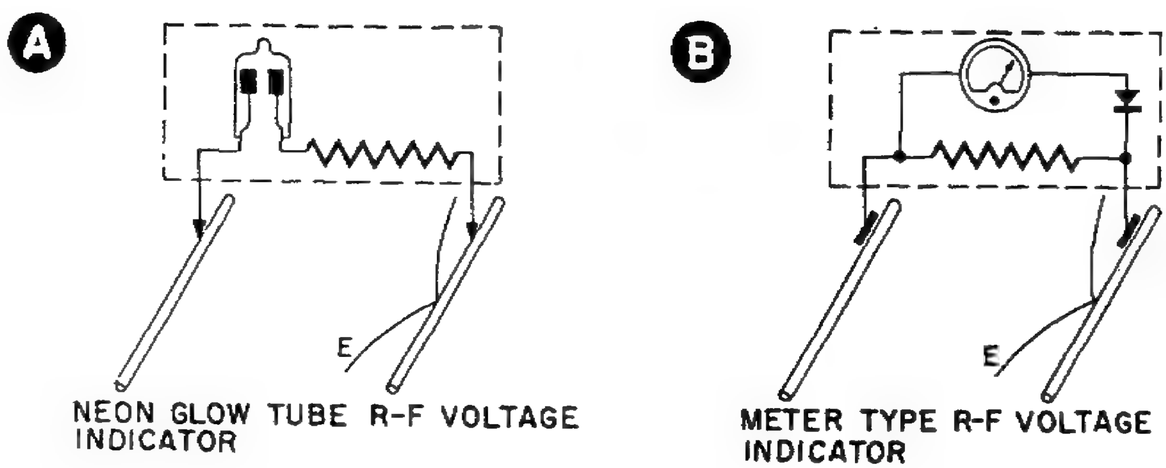
25. Measuring standing waves.

Now that we know what standing waves are and how they are produced, the next thing to learn is how to measure them. To make measurements on telephone and power lines, we use ordinary AC measuring devices and no difficulty arises. But, when we try to make these same measurements at ultra-high frequencies, the problem is different. For instance, a wire-wound calibrating resistor acts like an RF choke, while the familiar resistors used in radio sets may behave like inductors or capacitors. And, under certain conditions, an ordinary copper wire acts like an insulator. So that, if we put a conventional AC meter in a UHF circuit, we may be adding an unknown amount of capacitance or inductance. Our reading would be completely incorrect.

26. How can we measure standing waves at UHF frequencies?

a. One way that we can detect standing waves is by connecting a neon bulb across the line and sliding it along the line as in Part A of Figure 14. The neon bulb glows very brightly at the maximum voltage points. As you move the bulb along to the minimum voltage points, it becomes dimmer or completely dark.

Figure 14. Measuring Standing Waves of Voltage.



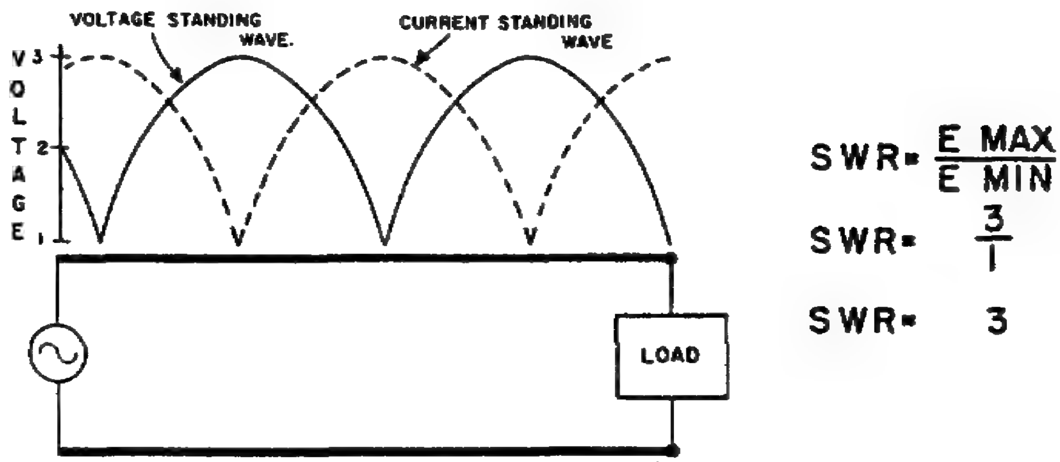
b. When it is necessary to measure actual voltage values, you will use an RF voltmeter or a sensitive DC ammeter with a crystal diode as the indicator. This method is shown in Part B of Figure 14. When measuring the voltage at various places along the line, you will find that the readings vary from some maximum value to some minimum value. The ratio of the maximum voltage to the minimum voltage reading is called the standing wave ratio or SWR.

c. For example, Figure 15 shows a transmission line with standing waves of current and voltage. The same effect occurs on both sides of the line. Standing waves are on the line because the load is not equal to the Zo of the line. Some of the RF energy is absorbed by the load, but most of it has been reflected. The voltage waveforms are plotted on a scale from 0 to 3 volts. The minimum voltage is 1 volt, and the maximum is 3 volts. The standing wave ratio is as follows:

$$SWR = \frac{Emax}{Emin} = \frac{3}{1} = 3$$

d. An SWR of 3 indicates that the load impedance is either three times greater than the Zo of the line or one-third the Zo of the line. In this case, the load impedance is one-third the Zo of the line because the voltage at the load is a minimum.

Figure 15. Measuring the Standing-Wave Ratio.



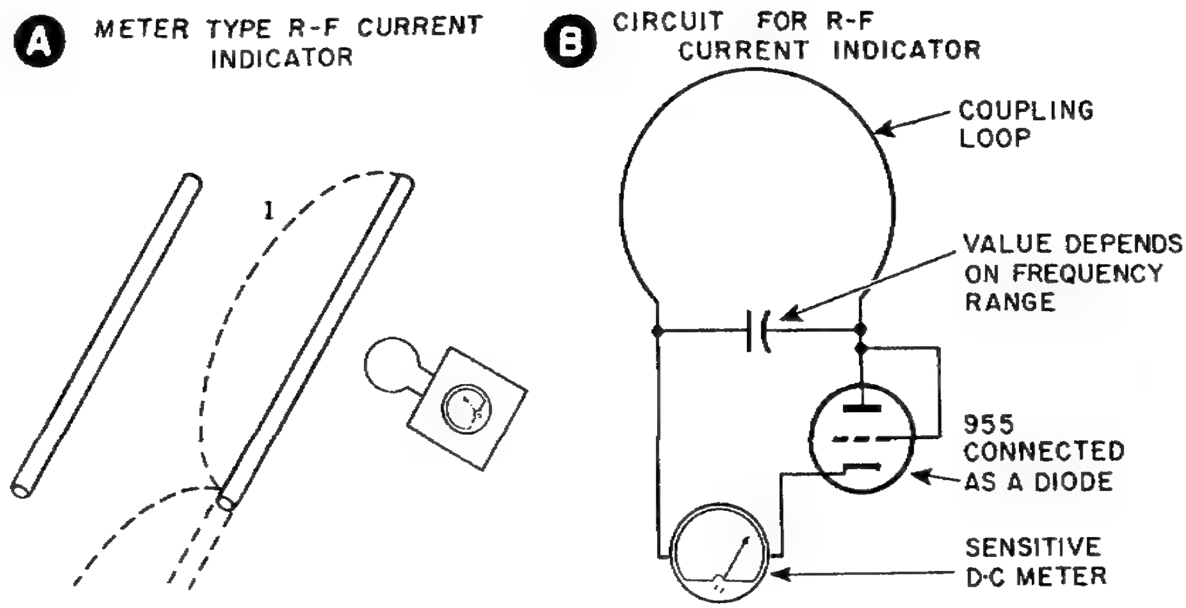
27. The SWR indicates an impedance mismatch.

a. The standing wave ratio is actually an indication of the degree of mismatch that exists between the load and the transmission line. When the transmission line is terminated in a resistive load equal to the Zo of the line, the maximum and minimum values of voltage are the same. In this matched condition, the SWR is 1 and the line is called a matched or flat line. There are no reflections; all the RF energy is absorbed by the load. A matched line is also called a non-resonant line.

b. When the load impedance is not equal to the Zo of the line, you will get an SWR greater than 1. The line is called a mismatched or resonant line. The resonant transmission line can then be represented by a series-resonant or a parallel-resonant circuits, depending on the type of load and length of line used. The SWR is highest when the line termination is either a short or an open circuit.

c. The standing-wave ratio may also be defined as the ratio between the maximum current and the minimum current. To measure the standing wave of current, an RF ammeter or a DC ammeter with a rectifier is used. The meter is connected to a loop of wire which is then placed close to the lines to couple into the magnetic fields. Part A of Figure 16 shows how this is done; Part B of Figure 16 shows the circuit for the meter.

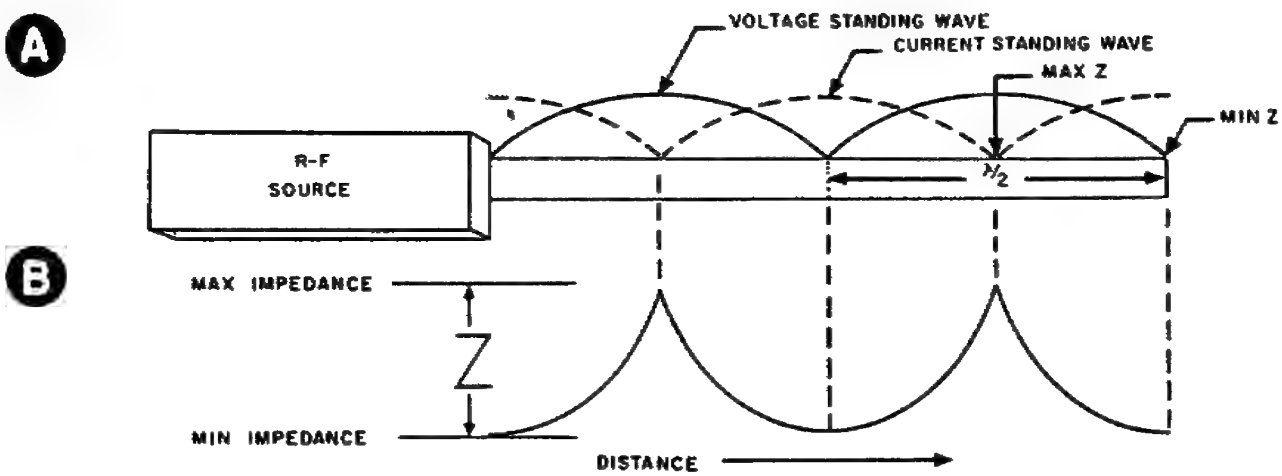
Figure 16. Measuring Standing Waves of Current.



28. The impedance varies along a mismatched line.

a. The impedance at any point on a transmission line is the ratio of the voltage to the current at that point. Figure 16 shows that the impedance varies along a shorted line. This happens because the waves reflected by the short cause the voltage and current to vary. Part A of Figure 17 shows the standing waves of voltage and current along a line which is one wavelength long. The voltage is minimum and the current maximum at the shorted end. The impedance at the shorted end is zero. One-quarter wavelength back from the short toward the generator, the impedance is maximum because of the maximum voltage and minimum current at that point. A half wavelength back from the short, the impedance is minimum again.

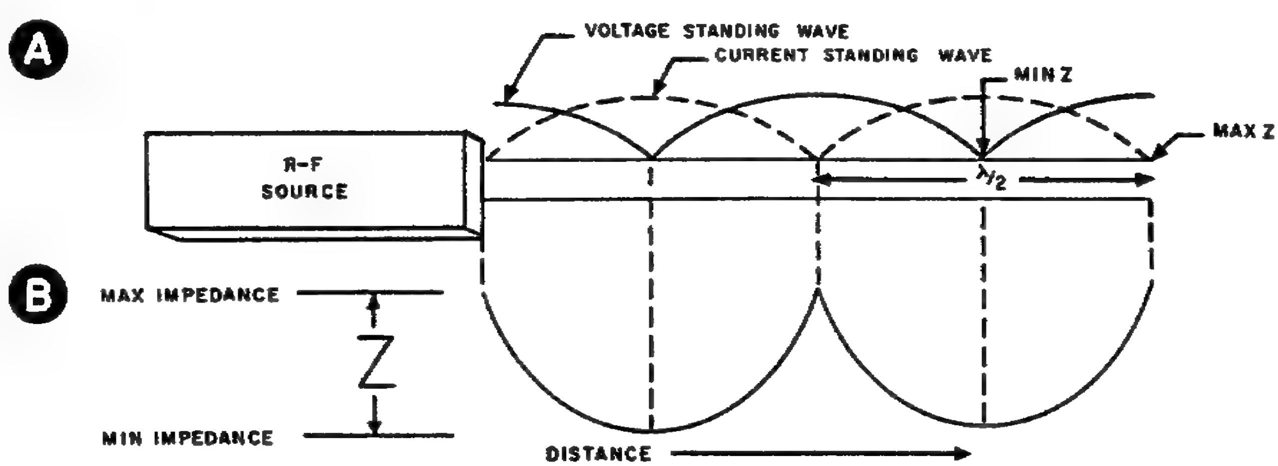
Figure 17. Impedance Variations Along a Shorted Transmission Line.



b. Plotting all the intermediate points between the minimum and maximum impedance values produces the curve shown in Part B of Figure 17. Notice that the impedance repeats itself every one-half wavelength.

c. Figure 18 shows how the impedance varies along an open-end transmission line. At the open end, the voltage is maximum and the current minimum. This condition shown in Part A of Figure 18, results in maximum impedance across the open end. One-quarter wavelength back from the open end, the impedance is minimum. The impedance is maximum again one-half wavelength back from the open end. The plot of impedance variations along the open end line is shown in Part B of Figure 18.

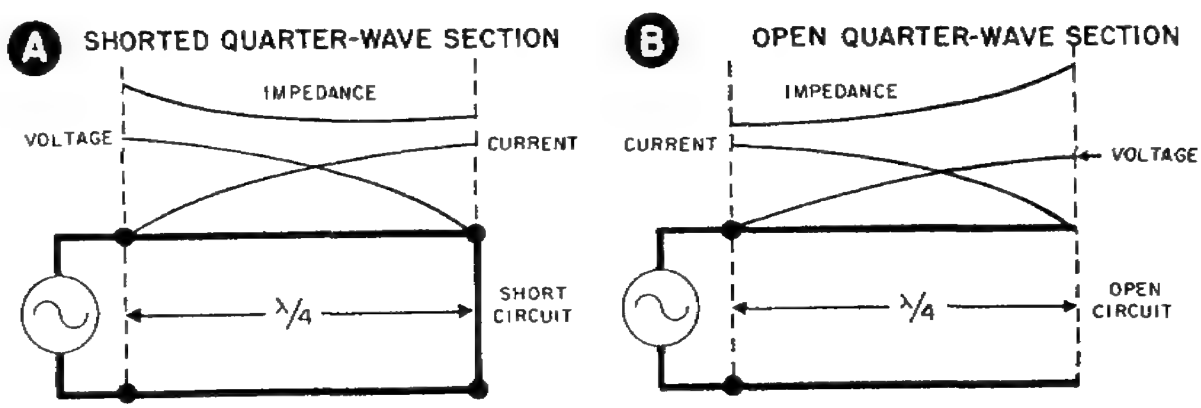
Figure 18. Impedance Variations on an Open-End Line.



29. A section of transmission line acts like a resonant circuit.

a. Because of these impedance variations, a section of transmission line can be used as a resonant circuit at ultra-high frequencies. For example, look at Part A of Figure 19 which shows the standing waves and impedance variations on a short-circuited, quarter-wave transmission line. The generator feeds into a high impedance because the voltage is maximum and the current is minimum at that point. A parallel-resonant circuit has the same characteristics; that is, high voltage, low current, and high impedance. So the quarter-wave line is now equivalent to the parallel-resonant circuit. Remember, however, that the quarter-wave line acts as a parallel-resonant circuit only at the frequency which makes the transmission line one-quarter wavelength long. At other frequencies, the line is not a quarter wavelength, so the impedance decreases.

Figure 19. Voltage, Current and Impedance Variations on a Quarter-wave Transmission Line.



b. Part B of Figure 19 shows voltage, current, and impedance variations on an open-circuited, quarter-wave transmission line. There is high impedance at the open end. But at the generator, the impedance is low because the voltage is low and the current is high. Low voltage, high current, and low impedance are the characteristics of a series-resonant circuit. So an open-circuited, quarter-wave line acts like a series-tuned circuit.

30. Summary of the quarter-wave line.

a. A short-circuited, quarter-wave line acts as a parallel-tuned circuit. It presents a high impedance to the generator.

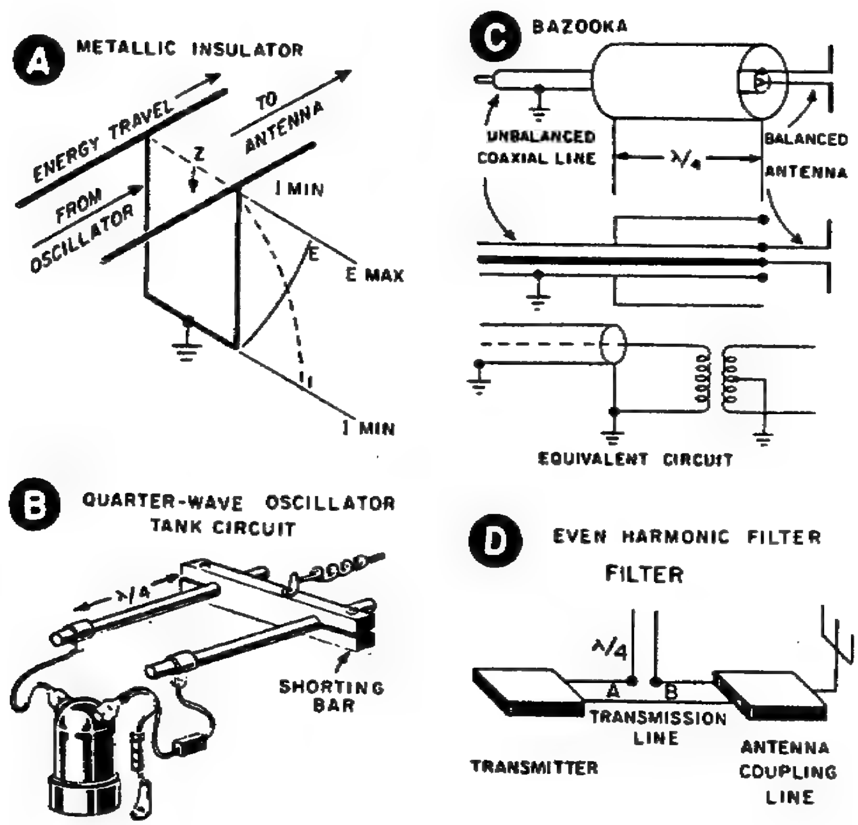
b. The open-circuited, quarter-wave line acts like a series-tuned circuit. It presents a low impedance to the generator.

c. The quarter-wave line inverts the load, that is, a short circuit looks like an open circuit to the generator, while an open circuit appears as a short circuit.

d. The voltage and current are shifted 90 degrees because of the inverting properties of the quarter-wave line.

e. Common applications of the quarter-wave section of transmission line are described and illustrated in Figure 20.

Figure 20. Quarter-Wave Line Applications.



(1) Figure 20, Part A.

(a) Energy from main transmission line enters the quarter-wave section.

(b) Standing waves of E and I are set up.

(c) RF energy meets a high Z at the opening of the quarter-wave section.

(d) Quarter-wave section also acts as a sturdy mechanical support for the main line.

(2) Figure 20, Part B.

(a) A shorted quarter-wave section has the properties of a parallel-resonant circuit.

(b) The oscillator is tuned by adjusting the movable shorting bar.

(3) Figure 20, Part C.

(a) An antenna is usually balanced. Each side has the same impedance and voltage with respect to ground.

(b) A coaxial line is unbalanced. The outside conductor is at ground potential.

(c) The bazooka removes the ground potential at the point where the antenna is connected to the coaxial line.

(4) Figure 20, Part D.

(a) An open-end, quarter-wave section sets up a low Z at AB to the fundamental frequency.

(b) RF energy at the fundamental frequency passes to the antenna.

(c) The filter becomes a half-wave section at the second harmonic. It sets up a high impedance at AB.

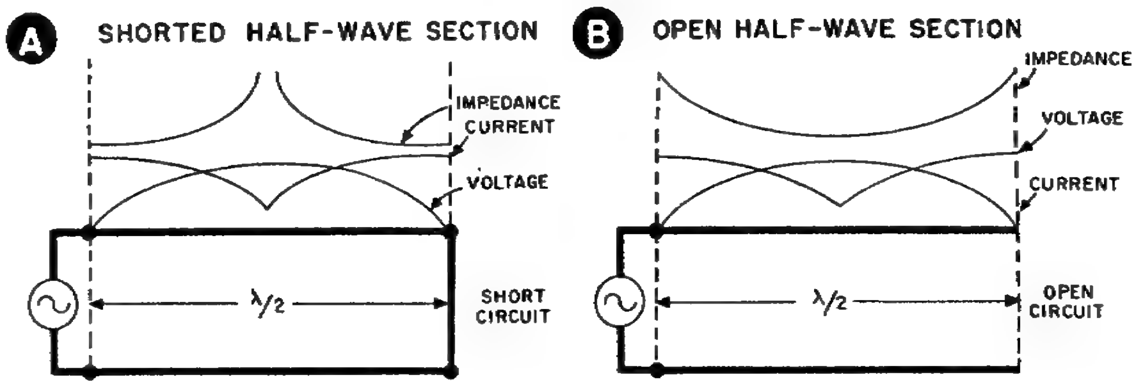
(d) The second harmonic does not pass on to the antenna.

31. The half-wave section of transmission line.

a. The half-wave section of a line is really an extension of the quarter-wave section. So, if you understand how the quarter-wave section works, you will have little difficulty with the half-wave section. Figure 21 shows the standing-wave and impedance variations on a half-wave section of line. Notice that whatever conditions appear on the load end of the line are repeated at the generator or source end. For example, look at Part A of Figure 21 which shows the voltage,

current, and impedance variations along a short-circuited, half-wave section. The impedance at the short circuit is minimum because the voltage, current, and impedance variations along a short-circuited, half-wave section. The impedance at the short circuit is minimum because the voltage is minimum and the current maximum. These same conditions are repeated at the generator. At the generator, the impedance is minimum also. The half-wave section appears to the generator as a series-tuned circuit.

Figure 21. Voltage, Current and Impedance Variations on a Half-Wave Section of Transmission Line.



b. The open-circuited, half-wave section has the characteristics of a parallel-tuned circuit. Part B of Figure 21 shows that the voltage is maximum and the current minimum at the open end. These conditions result in a high impedance at that point. One-half wavelength back at the generator, these conditions are repeated. The generator appears to be working into a parallel-tuned circuit with the characteristics of high voltage, low current, and high impedance.

32. Summary of the half-wave line.

a. The short-circuited, half-wave section acts as a series-tuned circuit. It presents a low impedance to the source.

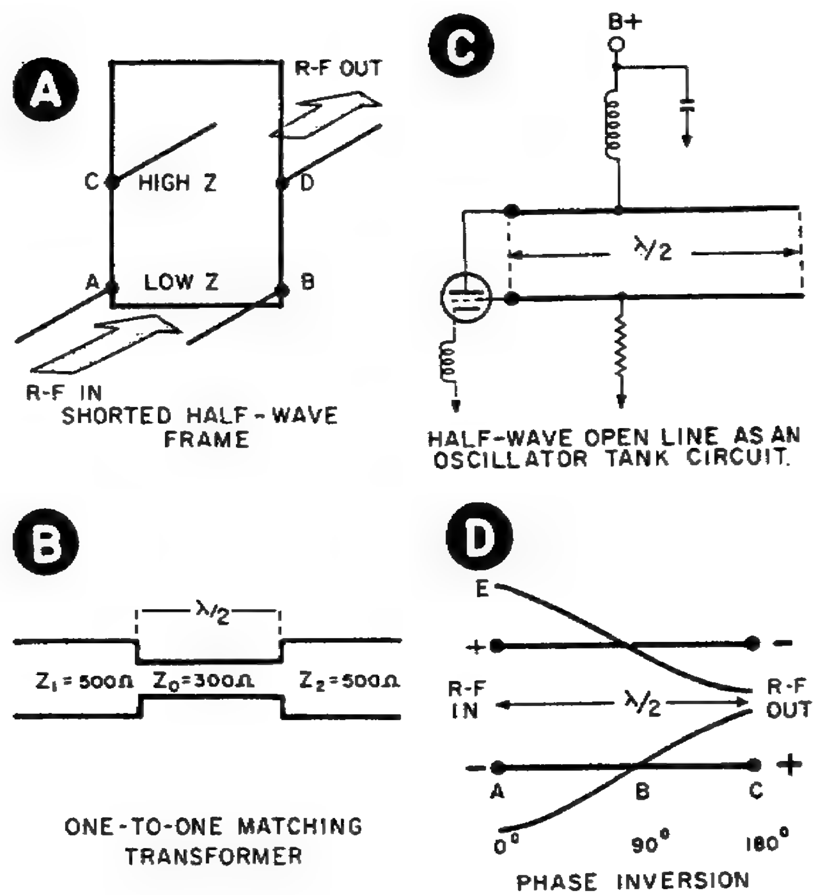
b. The open-circuited, half-wave section acts like a parallel-tuned circuit. It presents a high impedance to the source.

c. The half-wave line repeats the load. A low resistive load appears as a low resistance to the generator. A high resistance at the load end appears as a high resistance to the generator.

d. Voltage and current are shifted 180 degrees.

e. Common applications of the half-wave section of transmission lines are described and illustrated in Figure 22. When studying these applications, keep in mind the important facts given about the half-wave sections.

Figure 22. Half-Wave Line Applications.



(1) Figure 22, Part A.

(a) A low Z line is matched to a high Z line.

(b) The half-wave frame is excited at AB setting up standing waves of E and I.

(c) The Z is zero at the ends and maximum in the center.

(d) The low Z line is attached to a low Z point on the frame.

(e) The high Z line is attached to a high Z point in the frame.

(2) Figure 22, Part B.

(a) A half-wave section repeats the input impedance at the output.

(b) A 300-ohm half-wave section connects two lines having a Zo of 500 ohms.

(c) A proper impedance match results regardless of the Zo of the half-wave section.

(3) Figure 22, Part C.

(a) Open-ended, half-wave section acts like a parallel-resonant tank circuit.

(b) Voltage is maximum at the open ends of the section.

(c) The supply voltage (B+) and the grid-leak resistor are attached at points of minimum RF voltage.

(d) No tuning arrangement provided.

(4) Figure 22, Part D.

(a) The voltage is maximum at the input terminals (A).

(b) One-quarter wavelength away, the voltage drops to zero (B).

(c) Beyond B, the voltage again increases but in opposite phase.

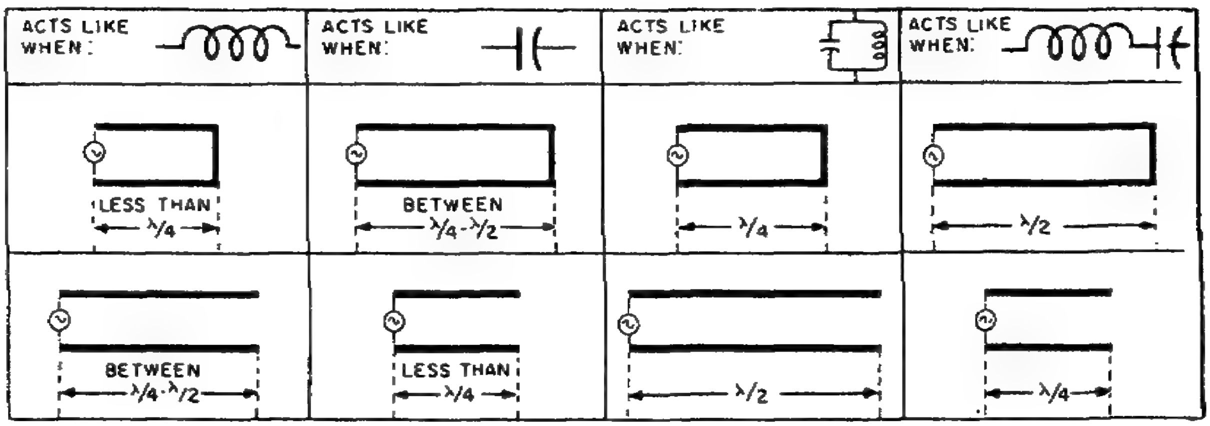
(d) The voltage at the output terminals (C) has the same amplitude as the voltage at A, but is 180 degrees out of phase with it.

33. Transmission lines other than one-quarter or one-half wavelength.

So far, we have emphasized the quarter-wave and the half-wave sections of transmission lines. However, there are many applications that use lengths of transmission lines other than the two we have discussed. Figure 23 summarizes the properties of transmission lines that are one-half wavelength or less. The chart shows you that a short-circuited

section of transmission line that is less than a quarter wavelength can take the place of an inductor, at the ultra-high frequencies. An actual coil having a specific amount of inductance would be too small to be practical at such high frequencies.

Figure 23. Properties of Transmission Lines One-Half Wavelength or Less.



Learning Event 2:
ARTIFICIAL TRANSMISSION LINES

1. General.

a. A transmission line is used to guide RF energy from one place to another with a minimum loss of energy. In addition, sections of RF transmission lines are used as coils and capacitors. For example, an open circuited quarter-wave line acts as a coil and capacitor in series. An open-circuited, half-wave line acts as a coil and capacitor connected in parallel.

b. Since a transmission line acts like a combination of coils and capacitors, it follows that we can connect coils and capacitors in arrangements that will act like transmission lines. We call this circuit arrangement of coils and capacitors artificial transmission lines (ATL).

c. Two major ATL uses we will discuss in this text are:

(1) As pulse-forming networks (PFN), to form pulses used in radar.

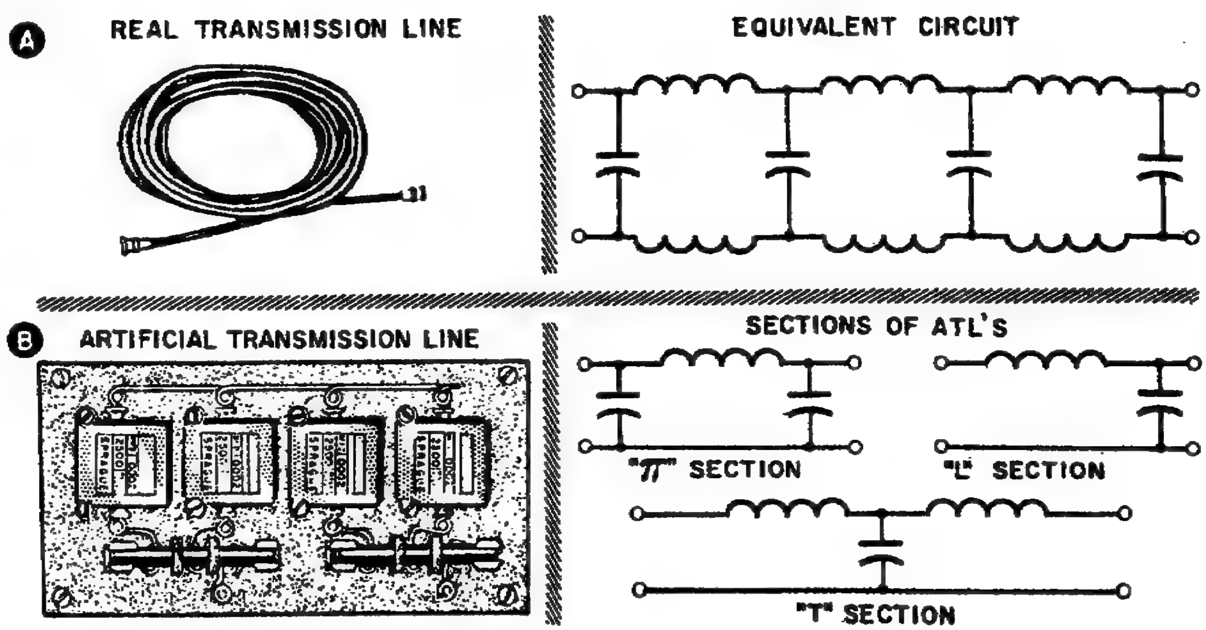
(2) As delay lines to delay pulses.

2. Comparing real and artificial transmission lines.

a. Figure 24 shows how ATLs compare to real transmission lines. Transmission lines are similar to ordinary circuits in that they have inductance, capacitance, and resistance.

b. Part A of Figure 24 shows a real transmission line and its equivalent circuit. The properties of a transmission line are distributed throughout the line and can be considered as a number of coils connected in series and capacitors shunted across the line. The coils have a small amount of resistance and the capacitors have some conductance. To make an ATL, all you need are coils and capacitors that have the same lumped inductance and capacitance value as in a real line. Part B of Figure 24 shows how coils and capacitors can be connected in "pi," "L," or "T" sections. Any number of sections may be used to make an ATL. Both the real and artificial lines oppose current flow.

Figure 24. Comparison of Real and Artificial Transmission Lines.



3. Characteristic impedance and characteristic resistance.

a. A real transmission line presents a characteristic impedance (symbolized by Zo) to the flow of RF energy. This characteristic impedance of a real line is equal to the square root of the inductance divided by the capacitance. This is expressed as the formula:

$$Zo = \sqrt{L/C}$$

b. Artificial transmission lines also present opposition to RF energy called characteristic resistance. We use the term characteristic resistance to indicate the impedance of an artificial transmission line. The symbol for characteristic resistance is Rc. As in a real line, the opposition is equal to the square root of the inductance divided by the capacitance. The formula is the same as for a real line:

$$Rc = \sqrt{L/C}$$

4. Transmission lines delay voltage.

a. When voltage is applied to the input terminals of a real line, a definite amount of time passes before the voltage appears at the output. This is known as time delay (TD). In a real line, the time delay depends upon the distributed inductance and capacitance per unit length of time and the length of line used. The time delay of a real transmission line is equal to the length of the line times the square root of L and C. The formula for determining the TD of a real line is as follows:

$$TD = \text{length}\ \sqrt{LC}$$

b. Transmission line manufacturers use one foot as a unit length. Since the values of L and C per foot are very small, it takes many feet of real line to delay a pulse just a fraction of a second. For example, let's use the TD formula to find out how long it takes a pulse to travel along 1,000 feet of line that has a distributed inductance of .2 microhenries, and a distributed capacitance of 20 uuf per foot. Using the formula, we get:

$$TD = \text{length}\ \sqrt{LC}$$

Substituting the values given:

$$TD = 1000\ \sqrt{(.2 \times 10^{-6})\ (20 \times 10^{-12})}$$

Multiply L and C:

$$TD = 1000\ \sqrt{4 \times 10^{-18}}$$

(The square root of 4×10^{-18} is 2×10^{-9} which equals $.002 \times 10^{-6}$.)

The result is:

$TD = 1000 \times .002 \times 10^{-6}$ seconds
or
$TD = 2$ microseconds

c. This example shows that the use of real line to delay a pulse 2 microseconds would be awkward to say the least. Even if you roll the 1,000 feet of transmission line to coil form, it will be very bulky. If you wanted to increase the delay, you would have to make the line even longer. You could not change the L and C without making the line longer because these are characteristics of the line. With artificial transmission lines, it's a different story. An ATL can be built to occupy a small space and still have the same characteristics as several miles of real transmission line. In other words, a combination of L and C components (ATL) can be used to obtain the same time delay as that provided by a real transmission line of any given length.

5. An ATL can be substituted for a real line.

a. The time delay you get from an ATL depends upon the lumped values of inductance and capacitance per section and the number of sections used.

b. To find the time delay of an ATL, multiply the square root of the L and C per section by the number (N) of sections used, using the formula: $TD = N\sqrt{LC}$. One coil and capacitor can be used instead of many feet of line. To increase the delay, merely increase the values of L and C, or add more sections. Three to eight sections are used for most radar applications.

6. Comparing characteristics.

So far, you have learned that artificial transmission lines can be used as substitutes for real transmission lines for certain applications in radar and other RF systems. The major uses of ATL are as pulse-forming lines and delay lines. ATL have the same characteristics as real transmission lines. A comparison of the characteristics is given as a summary in Figure 25.

Figure 25. Comparing Characteristics of ATL and Real Transmission Line.

Characteristics	Real line	Artificial line
1. Properties.	Distributed L, C, R, G.	Lumped L and C.
2. Opposition to RF energy.	Characteristic impedance- $Zo = \sqrt{\frac{L}{C}}$	Characteristic resistance- $Rc = \sqrt{\frac{L}{C}}$
3. Time delay.	Square root of distributed L and C, times length of line: $TD = \text{length} \sqrt{LC}.$	Square root of lumped L and C, times number of sections: $TD = N \sqrt{LC}.$

7. Radar systems need rectangular pulses.

The magnetron, under the control of the modulator, generates short, regularly spaced pulses of RF energy. The modulator controls the operation of the magnetron by supplying it with high-voltage, rectangular pulses of DC. That is, the modulator controls the shape and duration of the pulses. The accuracy of the radar set depends on the shape of these pulses. We need the rectangular pulses that have constant amplitude and steep edges. The amplitude of the pulse must be constant to keep the magnetron oscillating at its assigned frequency and correct power output. The leading edge of the pulse must be as steep as possible for accurate ranging. The trailing edge must also be steep to ensure minimum range determination.

8. ATL produce pulses used in radar.

a. An ATL can produce a nearly rectangular pulse having an amplitude of several thousand volts. A multivibrator that could give the same output would weigh a hundred pounds or more and occupy considerable space. The ATL, of course, consists of only a few inductors and capacitors and takes up much less space. Another advantage is the accuracy with which the amplitude and duration of the pulse can be delivered.

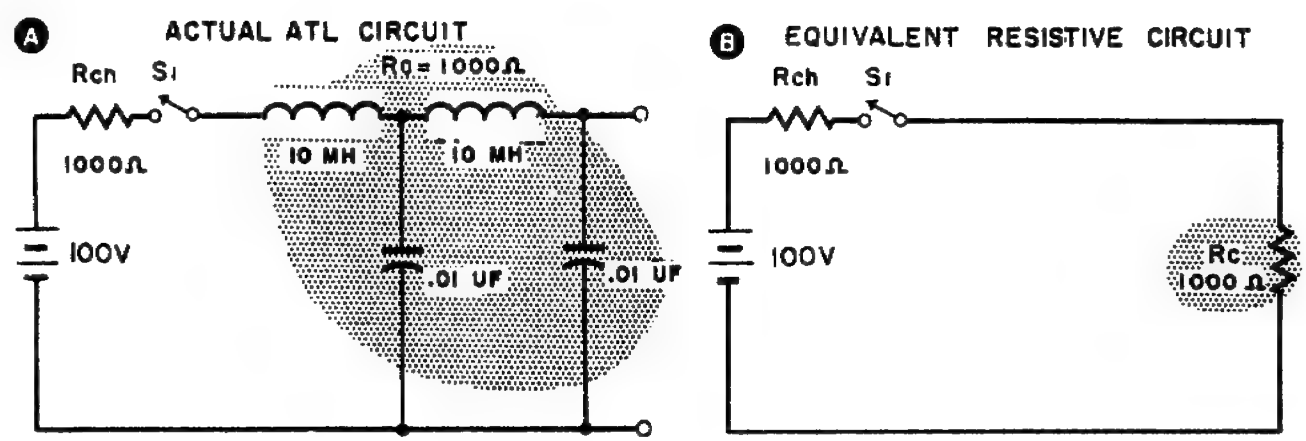
b. You get a large amplitude, short duration, radar modulating pulse by charging and discharging an ATL. The resulting pulse is often powerful enough to drive a magnetron directly. If it isn't, the pulse can be further shaped and amplified by electron tube stages.

c. A radar set uses an ATL that has a characteristic resistance equal to the resistance of the ATL high-voltage charging source. When the high voltage is applied to the ATL, the ATL charges very rapidly in a special way that forms the pulse we need.

9. Charging an ATL when its characteristic resistance equals the voltage source resistance.

a. Part A of Figure 26 shows a 100-volt battery connected to an ATL consisting of two "L" sections. Rch represents the source resistance and Rc the characteristic resistance of the ATL. In this case, they're both 1,000 ohms. Switch 51 connects the sources voltage to the ATL. An equivalent circuit is shown in Part B of Figure 26, where Rc is represented as a 1,000-ohm resistor.

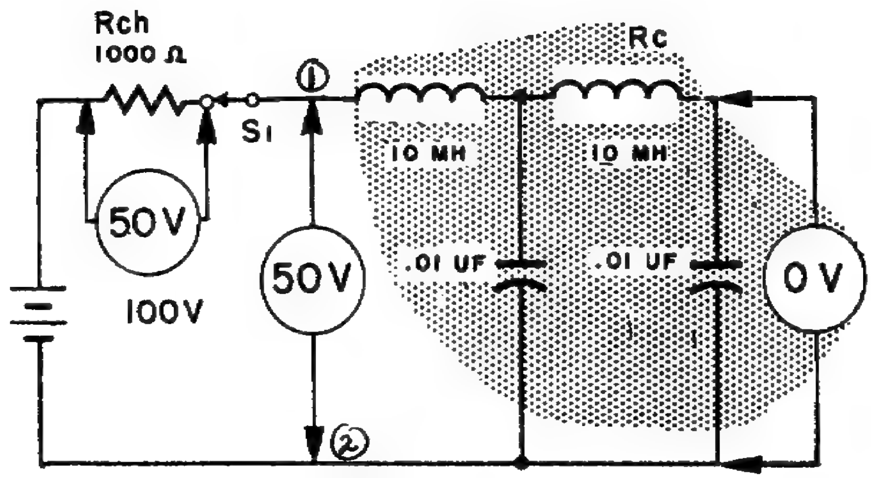
Figure 26. Double "L" Section ATL and Equivalent Circuit.



b. Now, close switch S1 as shown in Figure 27. What happens? Well, Ohm's Law tells us that when two resistors of equal value are connected in series, half of the applied voltage appears across each resistor. Therefore, at the

instant the switch is closed, the voltage divides equally across Rch and Rc. This gives us 50 volts across resistor Rch, and also 50 volts between points (1) and (2) (Figure 27). Remember, we are speaking of the first instant of time after the switch is closed. The voltage has not yet started to travel along the ATL.

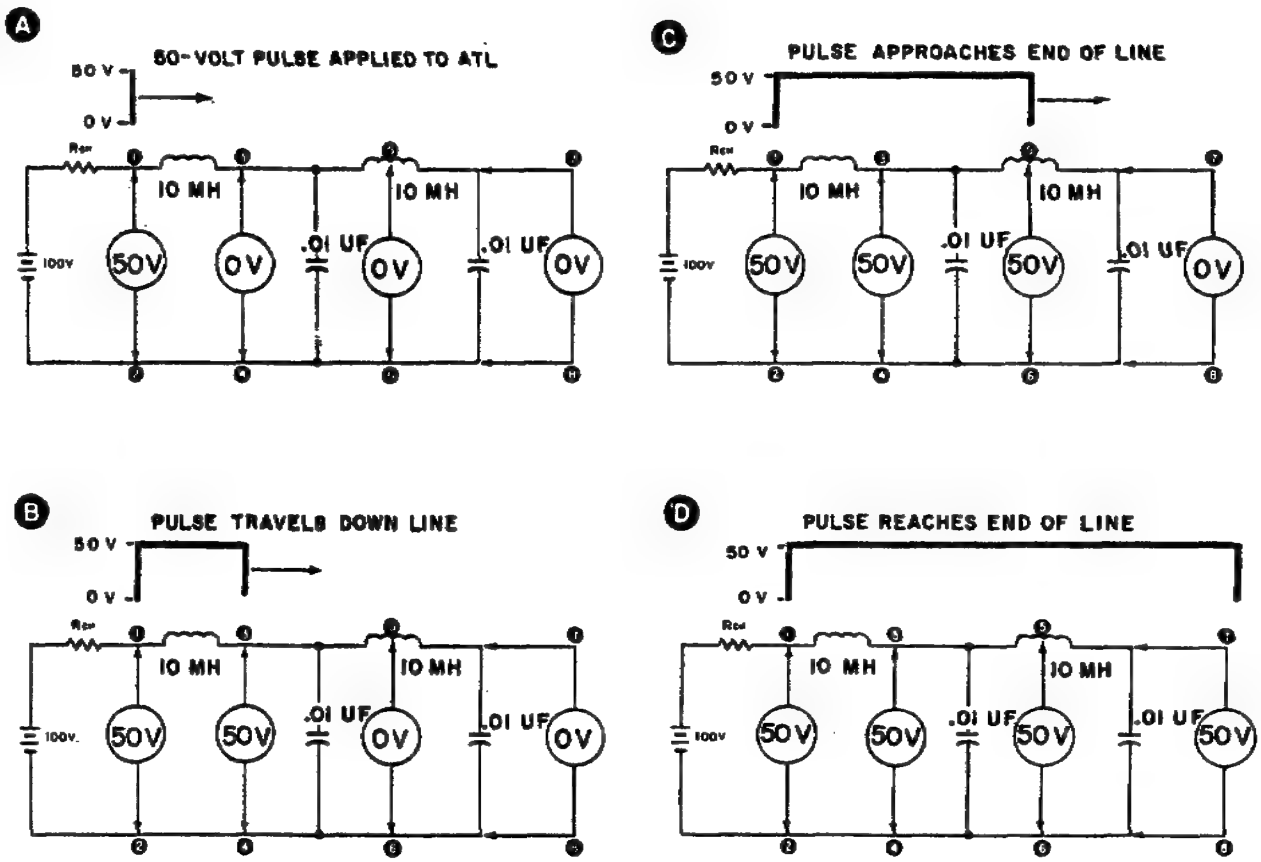
Figure 27. Double "L" Section ATL.



10. What happens as the 50 volt pulse travels along the line?

We will use four voltmeters to determine how the 50-volt pulse travels along the line. We already know from Figure 27, that at the first instant after the switch is closed, there are 50 volts between points (1) and (2). The direction of travel is shown in Part A of Figure 28.

Figure 28. The 50-Volt Pulse Travels Along the ATL.



a. In the next instant, the 50-volt pulse starts to travel along the line and we see in Part B of Figure 28 that the 50 volts is now present across points (3) and (4).

b. Still, another instant of time later and our voltmeters in Part C of Figure 28 tell us the pulse has traveled as far as points (5) and (6).

c. Finally, as shown in Part D of Figure 28, the 50-volt pulse has traveled to points (7) and (8) at the end of the line.

11. What happens at the open end of the line?

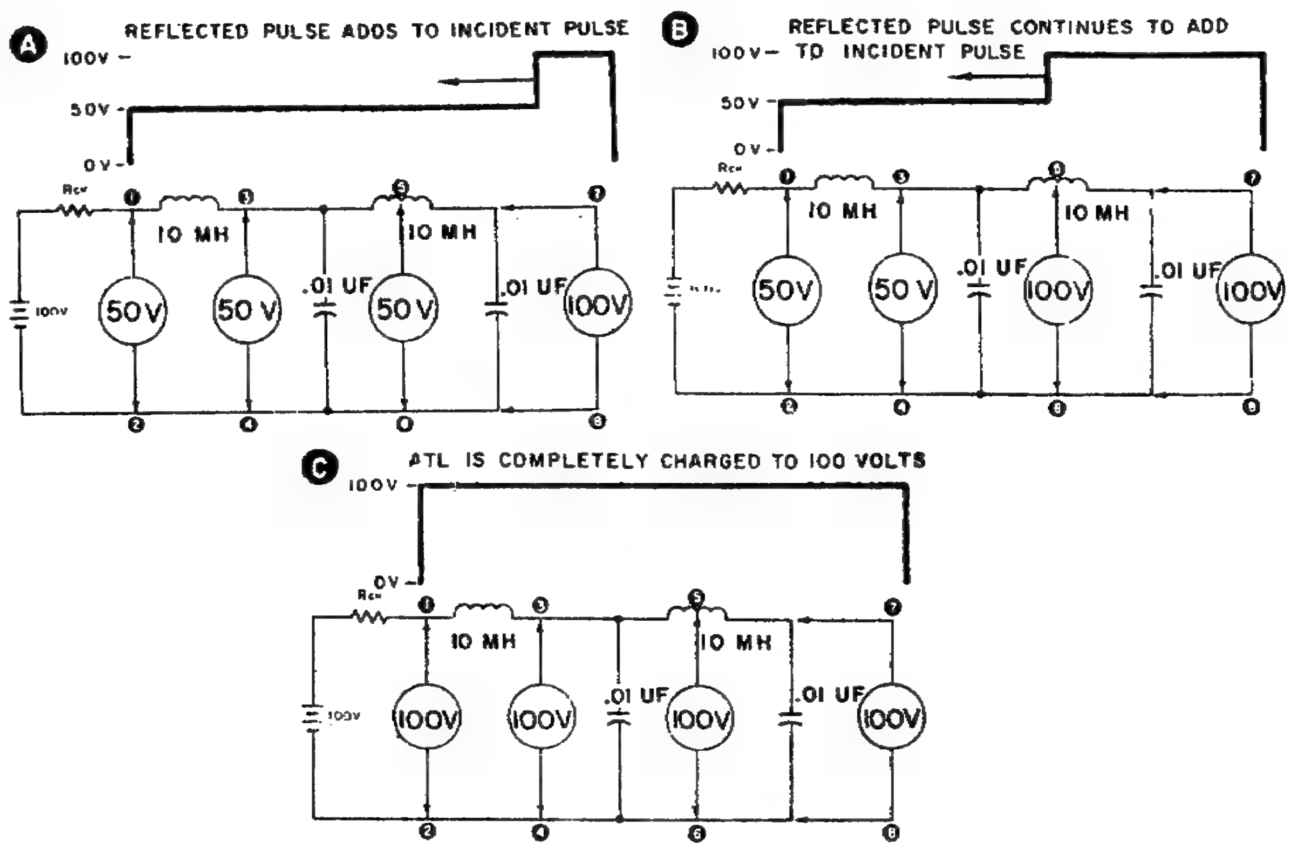
When the energy traveling along the transmission line reaches the open end of the line, the current drops to zero. This rapid change in current induces a voltage that is equal to the original (incident) wave in amplitude and polarity.

We call this new energy a reflected wave because it is reflected back to the source. In the example we are using, a reflected pulse of 50 volts adds to the original 50 volts, making the total voltage at the open end 100 volts.

12. The reflected wave travels toward the battery.

The 100 volts across the open end of the ATL is considered a new source voltage. It moves in a direction opposite to that of the original (incident) energy. Let's observe the voltmeters again and see what happens as the reflected wave moves toward the battery.

Figure 29. The Pulse is Reflected.



a. Part A of Figure 29 shows the line at the instant when the reflected voltage adds to the original voltage.

b. We see in Part B of Figure 29 that the reflected 50 volts now appears at points (5) and (6), making the meter at these points read 100 volts.

c. The 100-volt pulse continues along the line and arrives at points (3) and (4). Finally, as shown in Part C of Figure 29, the complete ATL is charged to 100 volts, twice the voltage originally applied.

13. Determining the time delay.

a. To determine the time it took for the pulse to get from one end of the line to the other, we use the time delay formula, TD = N LC. In this case, the value of each coil is 10 mh and the value of each capacitor is .01 uf. The ATL has two sections. Calculating, we get:

$$TD = 2\sqrt{(10 \times 10^{-3})\quad(.01 \times 10^{-6})}$$

$$TD = 2\sqrt{.1 \times 10^{-9}} = 2\sqrt{1 \times 10^{-10}}$$

$$TD = 2 \times 10^{-5}$$

$$TD = 20 \text{ microseconds}$$

b. The pulse took exactly 20 microseconds to get from the battery end of the line to the open end. The values of L, C, and N are the same for the returning pulse; therefore, it takes 20 microseconds for the reflected pulse to return. The complete action takes 40 microseconds. Thus, the time required to charge an ATL is equal to twice the delay time of the line because the voltage has to go to the end of the line and back. The voltage on the line will remain at 100 volts until the line is discharged.

14. A review of the main points thus far.

a. ATL have the same electrical characteristics as real transmission lines but take up much less space.

b. ATL are used as pulse-forming networks in radar systems.

c. A pulse takes a definite amount of time to travel from one end of an ATL to the other.

d. An ATL terminated in an open circuit will charge to the supply voltage in twice the delay time of the line.

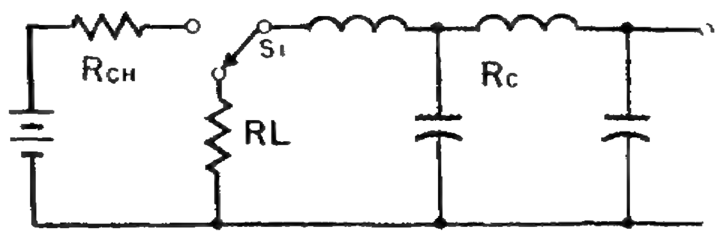
15. Now, let's discharge the ATL.

a. You have just seen how to charge an ATL and that an ATL charges to the supply voltage in a definite amount of time. It takes two TDs to charge the ATL when the characteristic resistance of the ATL equals the source resistance.

b. Now, if we connect a resistor (or some other component) across the ATL, it provides a discharge path. In a radar set, the main purpose of the ATL pulse-forming network is to discharge through the magnetron. When the ATL pulse-forming network discharges through the magnetron, the magnetron generates the radar RF carrier.

c. The characteristic resistance RC of the charged ATL is equal to the source resistance Rch. We will discharge the ATL through a load resistor RL that has a resistance equal to both RC and Rch. In Figure 30, switch S1 disconnects the battery and connects the discharge path RL across the ATL.

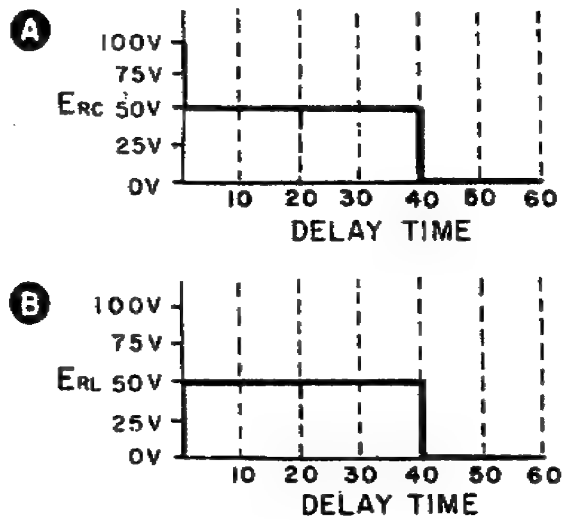
Figure 30. Discharge Path Connected to ATL.



d. Rc and RL are equal. So, the 100-volt charge divides equally, placing 50 volts across Rc and 50 volts across RL. This means that the 100-volt charge across the ATL goes in a negative direction, dropping from 100 volts to 50 volts. The negative-going 50 volts travels along the line and is reflected in the same polarity (negative direction) and amplitude. The negative-going 50 volts travels along the line and is reflected in the same polarity (negative direction) and amplitude. The incident and reflected voltages add (-50 volts and +50 volts) and the voltage across the line drops to zero. Part A of Figure 31 shows that the voltage across the ATL (Rc) drops to 50 volts for two TDs and then drops to zero.

e. Part B of Figure 31 shows the pulse across the load resistor (RL). The instant switch 51 is closed; the voltage across RL rises to 50 volts. It remains at 50 volts for two TDs and then drops to zero.

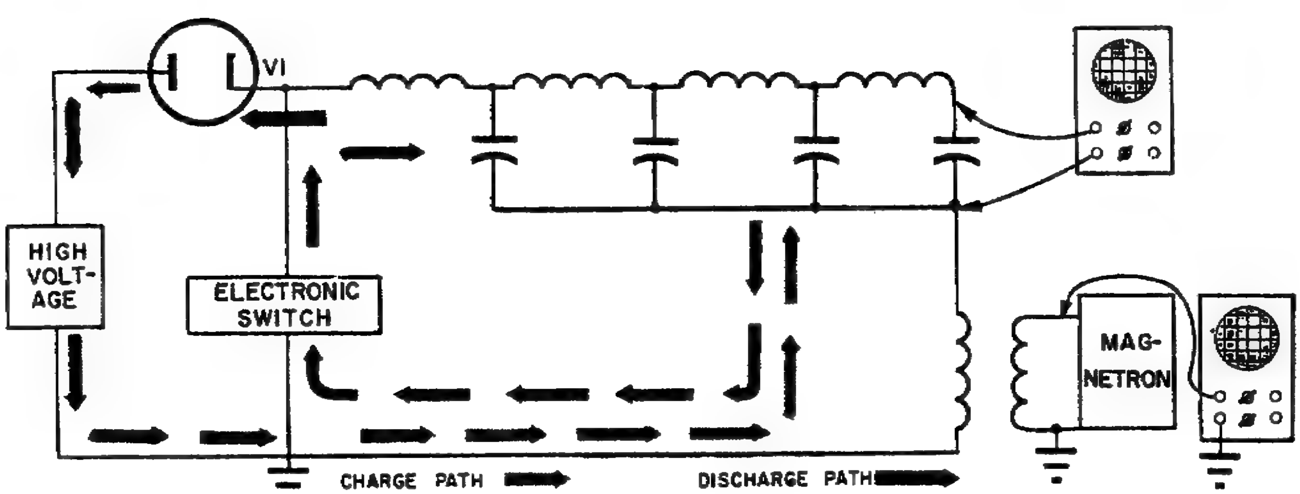
Figure 31. Waveforms of Discharging ATL.



16. A discharging ATL is used in radar modulators.

a. The pulse across the load resistor is the same kind that radar sets use for modulation. The pulse amplitude is constant and the edges are steep. The time delay (width of the pulse) is determined by the values of L and C. A circuit block diagram for developing a rectangular pulse is shown in Figure 32.

Figure 32. Pulse Forming Circuit.



b. This block diagram of a high level radar modulation system is similar to the circuit we have been using. We replace the battery with a high voltage power supply of several thousand volts. The discharge path (RL) is replaced by the magnetron and its pulse transformer. An electronic switch replaces the mechanical switch. The diode is added to isolate the high voltage from the switch when necessary. The operation of the PFN and its circuit is as follows:

(1) At the first instant of time the electronic switch is an open circuit.

(2) The high voltage power supply charges the PFN through the pulse transformer primary and the isolation diode V1.

(3) The PFN charges to several thousand volts in two TDs.

(4) The PFN cannot discharge yet because current cannot flow from plate to cathode through the isolation diode V1.

(5) After the PFN is charged, a trigger spike short-circuits the electronic switch.

(6) Now there is a discharge path for the PFN, and current flows through the pulse transformer primary and electronic switch.

(7) After the PFN is completely discharged, the electronic switch is an open circuit again.

(8) The PFN recharges and is ready to be triggered again.

(9) The PFN is charged and discharged at the PRF of the radar.

17. Charge and discharge waveforms when Rc equals RL.

Notice the two oscilloscopes in Figure 32. One scope is connected across the PFN and the other scope across the load. Now we can watch the waveforms across both the PFN and the load.

(1) Both the PFN and the load are connected to the vertical deflection plates of the scopes. This gives us time reference along the horizontal axis and amplitude reference along the vertical axis. The graph in Part A of Figure 33 is the waveform of the charging PFN as seen on the scope. It

shows that, at the first instant of time, the PFN charges to the supply voltage. The PFN remains at the supply voltage for a time equal to two TDs. Then it rises to twice the supply voltage and remains at this potential until discharged. The figure on the scope is called a two-step waveform.

(2) Part B of Figure 33 shows the waveform across the load as the PFN discharges. The discharge current flows in a direction that gives us a negative voltage across the load. At the first instant of time, the voltage across the load goes from zero to the supply voltage. The voltage across the load remains at the supply voltage (negative polarity) for two TDs and then goes to zero again. Thus, we have a negative pulse that has a width equal to twice the delay time of the PFN. This pulse causes the magnetron to oscillate at the radar carrier frequency.

(3) In this circuit, we assumed that in the PFN, Rc equals RL. This is the ideal condition and desired for the PFNs you will be using. These are some important circuit characteristics in this case.

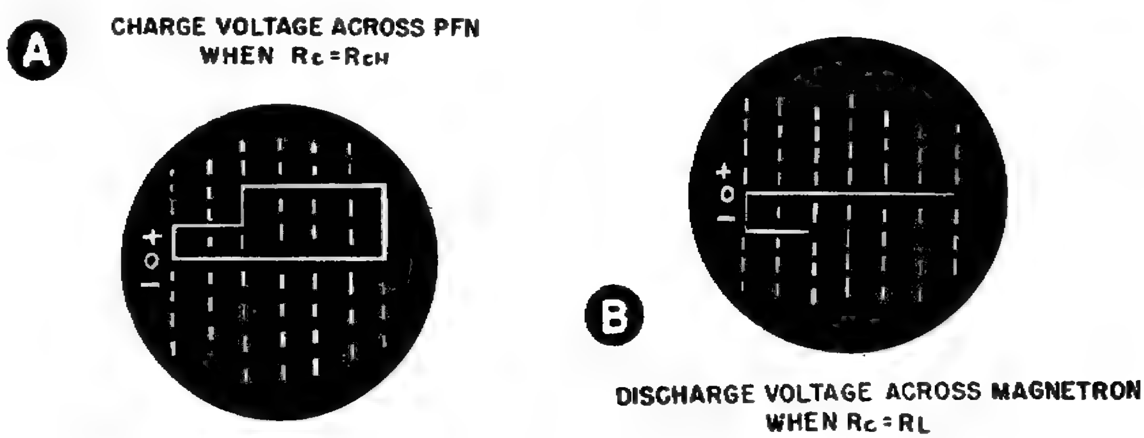
(a) A PFN produces a two-step waveform only when the PFN charges through a resistance equal to the characteristic resistance of the network.

(b) When a PFN is discharged through a resistance equal to the characteristic resistance of the network, a rectangular pulse is formed.

(c) The amplitude of the pulse is equal to one-half the voltage to which the line is charged.

(d) The pulse width is equal to two TDs.

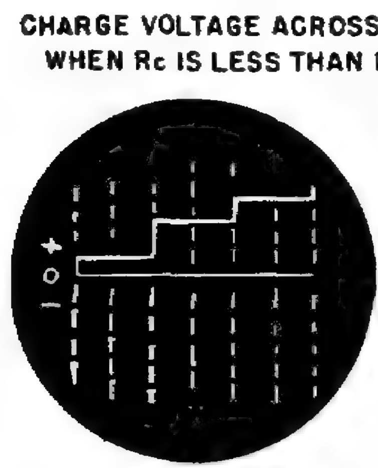
Figure 33. Waveforms of PFN.



18. When Rc does not equal Rch or RL in a PFN.

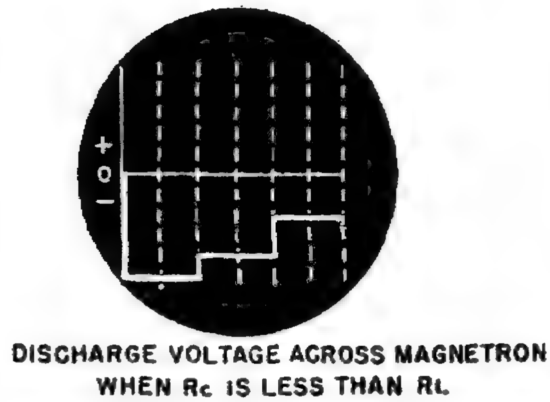
a. Charging waveform when Rc is less than Rch. Figure 32 shows the charge waveform of a PFN in which the characteristic resistance is less than the source resistance. Notice how the voltage charges up in steps. Each step after the second step is a little bit less than the preceding step. If you draw a line through the tips of each step, you see that the line is exponential. That's why this charge is called an exponential charge. If the ratio of Rc to Rch changes, the steps will change somewhat but it will still be exponential. You will see more steps on the scope if the mismatch becomes worse.

Figure 34. Rc less than Rch.



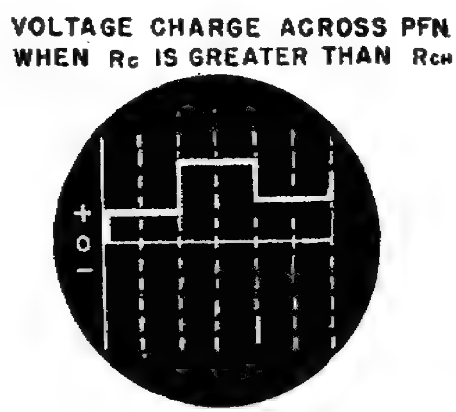
b. Discharging waveform when Rc is less than RL. Figure 35 shows the exponential discharge across a load (magnetron) that has a greater resistance than the characteristic resistance of its PFN. The oscilloscope shows how the voltage across the resistor is highly negative at the start of the discharge, and decreases in steps until it is completely discharged. As before, the ratio of Rc to RL determines the amount of discharge in each step. The greater the mismatch, the more steps there will be.

Figure 35. Rc less than RL.



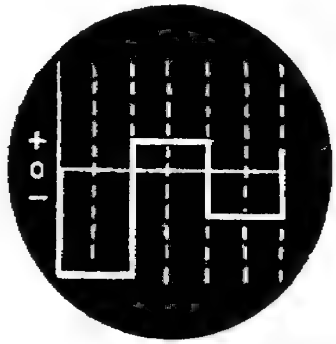
c. Charging waveform when Rc is greater than Rch. Figure 36 shows the dampened square wave pattern that appears across a PFN that has a characteristic resistance greater than the source resistance. If you see this pattern on the scope it means one of these two things: the characteristic resistance of the PFN has increased; or, the source resistance has decreased.

Figure 36. Rc greater than Rch.



d. Discharging waveform when Rc is greater than RL. Figure 37 shows the dampened square wave across a load that has less resistance than the characteristic resistance of the PFN. This pattern on a scope means one of two things: the characteristic resistance of the PFN has increased; or, the load resistance has decreased.

Figure 37. Rc greater than RL.



VOLTAGE DISCHARGE ACROSS MAGNETRON
WHEN Rc IS GREATER THAN RL

e. Summary of waveforms. The following chart summarizes the charge and discharge waveforms during the three conditions

Figure 38. Charge and Discharge Waveforms.

CHARGE

Conditions	Waveform
Rc equals Rch.	Two TD's, Two-step increase.
Rc is less than Rch.	More than two TD's, Exponential charge.
Rc is greater than Rch.	More than two TD's, Dampened square-wave pattern.

DISCHARGE

Conditions	Waveform
Rc equals RL.	Two TD's, Two-step decrease.
Rc is less than RL.	More than two TD's, Exponential discharge.
Rc is greater than RL.	More than two TD's, Dampened square-wave pattern.

19. An ATL is used to introduce delay.

When an ATL is used to delay a pulse some predetermined length of time, we call the ATL a delay line. You have seen how an ATL introduces this delay, and how the values of L and C determine the amount of delay. Let's look at some practical applications that require a definite time delay and use an ATL to produce it.

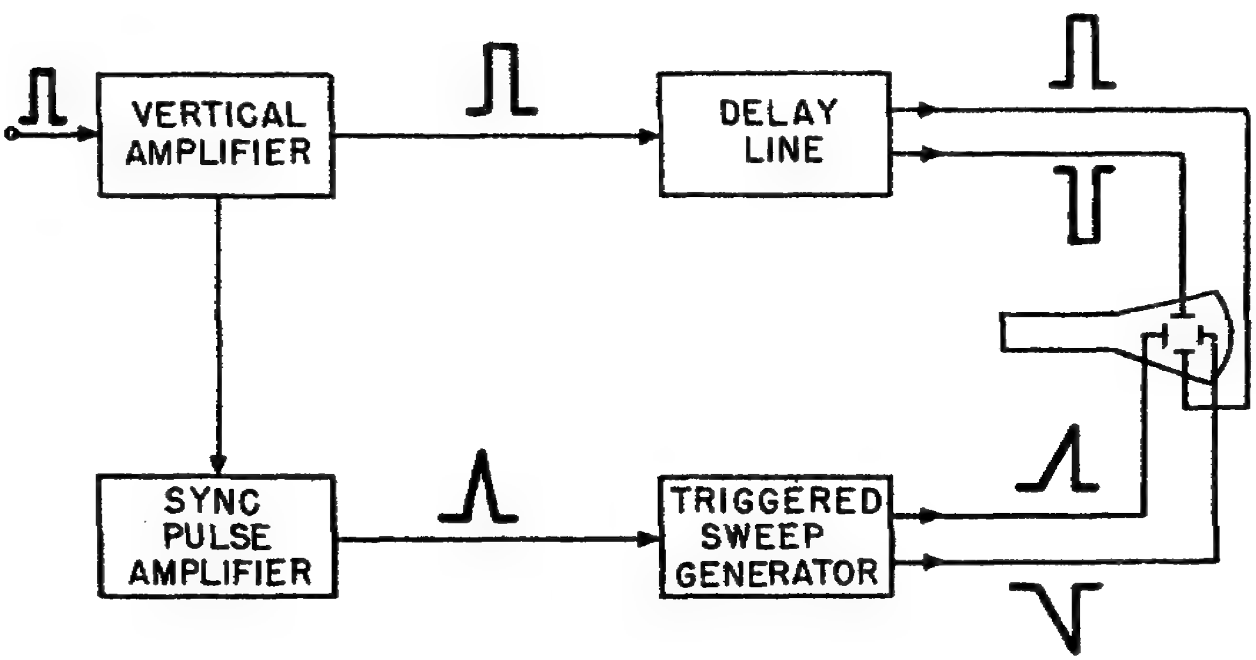
20. Delay lines are used in synchroscopes.

a. A synchroscope is an oscilloscope designed especially for the observation of non-periodic pulses and transients. A synchroscope has all the circuits of an oscilloscope plus two major additional circuits:

(1) A triggered horizontal sweep that sweeps the electron beam across the scope only when a pulse is applied to the vertical deflection plates.

(2) A delay line that prevents the pulse from causing a vertical deflection of the electron beam until shortly after the sweep has started. The block diagram of Figure 39 shows how these circuits are used in a synchroscope.

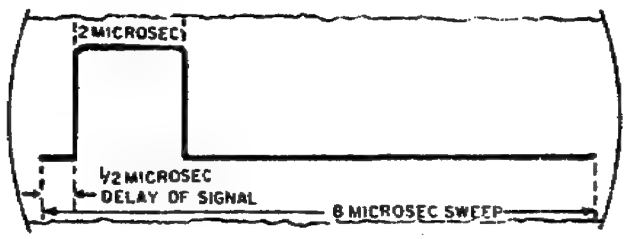
Figure 39. Synchroscope Delay Line and Triggered Sweep.



b. The applied pulse triggers the sweep generator. The pulse applied to the vertical amplifier input is amplified and fed to the sync pulse amplifier, where it is amplified again and formed into a spike. The spike triggers the sweep generator, which then sweeps the electron beam across the face of the scope. The sweep occurs when an incoming pulse triggers it. Since the sweep starts at the same instant the pulse is applied, the leading edge of the pulse may not appear on the face of the scope unless something is done to prevent this possibility. That's the purpose of the delay line.

c. After it is amplified, the applied pulse is fed to a delay line that delays the pulse by about one-half a microsecond. The applied pulse reaches the screen one-half a microsecond after the sweep starts across the face of the scope. So the complete applied pulse, including its leading edge, appears on the screen. Figure 40 shows the delayed pulse on the face of the scope.

Figure 40. Delayed Pulse on Scope.



21. Delay lines are used in time division multiplexing.

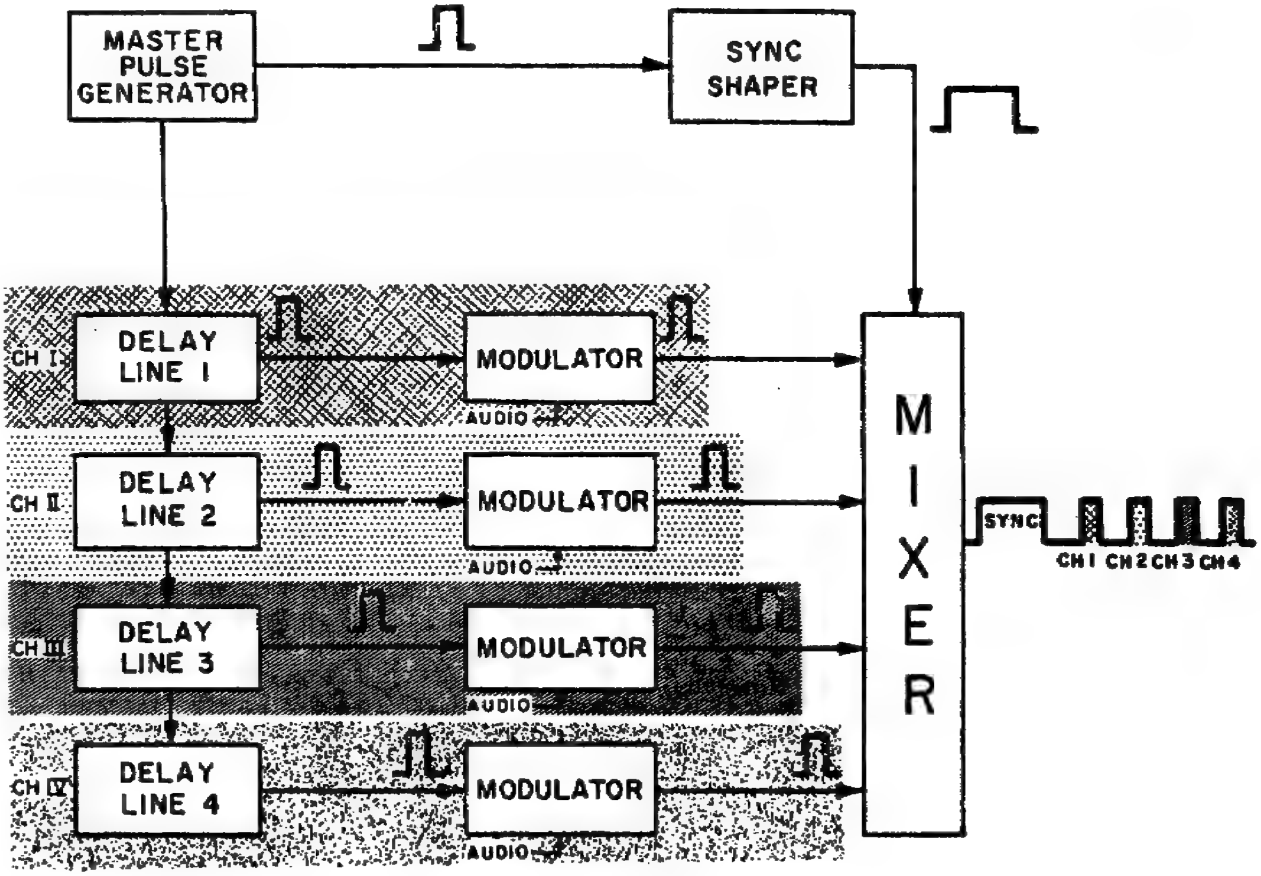
a. Time division multiplexing (TDM) is a system of communications that allows the transmission of many messages over a single RF carrier. One TDM system replaces many single-channel transmitters. This is done by converting up to twenty-three channels of audio information into a single pulse-position-modulated (PPM), time-division-multiplexed (TDM) pulse train. The train is then fed to an RF transmitter which transmits the signals to the desired location. At the receiving end, the pulse train is demodulated and the twenty-three channels of audio are relayed to their proper destinations.

b. The block diagram in Figure 41 shows how delay lines separate the pulses in a TDM transmitting set. The master pulse generator feeds a pulse to two stages as follows:

(1) The sync shaper stage widens the pulse for synchronizing the receiving multiplexer with the transmitting multiplexer.

(2) Then, the delay line sections in each channel delay the pulses before they are modulated. There are twenty-three delay line sections, one for each channel.

Figure 41. Block Diagram of Multiplexing Delay Line.



22. How the delay line works in a TDM transmitter.

a. In Figure 41, the master pulse generator feeds pulses to the delay line sections for each of twenty-three channels. Because of space limitations, only four channels are shown in the diagram. Then, each delay line section feeds a pulse into the modulator in the modulator in the same channel. Here's the important point, each delay line section introduces a 5.2-microsecond delay. This means that the pulse going to CH I modulator is delayed 5.2 microseconds. The pulse going to CH II modulator is delayed 10.4 microseconds because it passes through two delay line sections. Similarly, the pulse fed to CH III modulator is delayed 15.6 microseconds because it passes through the delay line sections of channels I, II, and III.

b. This process continues until there are twenty-three pulses, each separated by 5.2 microseconds in time, fed into the twenty-three different modulators. Each modulator combines the voice signal with the pulse and feeds the modulated pulse to the mixer. This produces a train of

twenty-three independently modulated pulses which are then impressed on a single RF carrier and transmitted. At the receiving end of the system, a reverse process takes place and the pulses are demodulated to produce the original voice signals.

PRACTICE EXERCISE
(Performance-Oriented)

In each of the following exercises, select the ONE answer that BEST completes the statement or answers the question. Indicate your solution by circling the letter opposite the correct answer in the subcourse booklet.

1. At radar and microwave frequencies, coaxial line sections are used in preference to two-wire sections because their

   a. velocity factor is higher.

   b. radiation losses are lower.

   c. dielectric is more efficient.

   d. circuits can be balanced in respect to ground.

2. Although the electrical properties of a transmission line are distributed evenly along the line, they can be represented as an infinite number of small values of series.

   a. inductance and capacitance plus shunt resistance and conductance.

   b. resistance and conductance plus shunt inductance and capacitance.

   c. inductance and resistance plus shunt conductance and capacitance.

   d. conductance and capacitance plus shunt inductance and resistance.

3. Assume that a radar set is designed to use a flexible coaxial cable with 4 characteristic impedance of 100 ohms and length of 10 meters to couple the RF energy from the transmitter to the antenna. If only 5 meters of the cable are used when installing the radar set, the characteristic impedance of the flexible cable will be

   a. 50 ohms.

   b. 100 ohms.

   c. 200 ohms.

   d. 400 ohms.

4. Assume that a coaxial transmission line is being used to transfer the RF output of a radar transmitter to the radar antenna. Maximum power will be transferred from the magnetron to the antenna when the

   a. coaxial line is terminated in a short circuit.

   b. standing wave ratio of the transmission line is greater than one.

   c. characteristic impedance of the transmission line matches the impedance of the magnetron and antenna.

   d. impedances of the magnetron and the antenna are less than the characteristic impedance of the transmission line.

5. Assume that a parallel-wire transmission line has been connected to an antenna having a resistive input impedance of 600 ohms. If the characteristic impedance of the transmission line is 500 ohms, what is the standing wave ratio of the voltage?

   a. 0.5/1.

   b. 1.00/1.

   c. 1.20/1.

   d. 1.83/1.

6. A transmission line will have a maximum standing wave ratio when the transmission line is terminated in

   a. a resistive load.

   b. an inductive load.

   c. a short or open circuit.

   d. an impedance equal to the characteristic impedance of the transmission line.

7. Resonant lines are often called tuned lines while nonresonant lines are called flat lines. What is one characteristic of tuned lines?

   a. Voltage is constant along the line.

   b. Reflected energy is present on the line.

   c. The voltage standing wave ratio is equal to one.

   d. The terminating impedance is equal to the characteristic impedance of the line.

8. Assume that the section of transmission line shown in Figure 42 is to be used as a circuit component in a radar set. What type of circuit has the electrical characteristics appearing between points A and B?

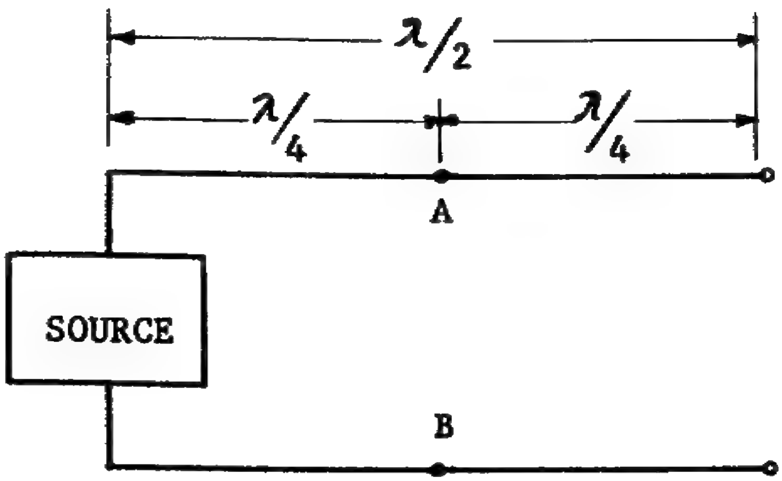
a. Capacitor and inductor in parallel.

b. Resistor and capacitor in parallel.

c. Inductor and capacitor in series.

d. Resistor and inductor in series.

Figure 42. Section of Transmission Line.



9. Assume that the quarter-wave section of transmission line shown in Figure 43 is being used as a supporting stub for the main transmission line. The impedance reflected back to the main transmission line at the fundamental frequency will resemble the impedance that is provided by a

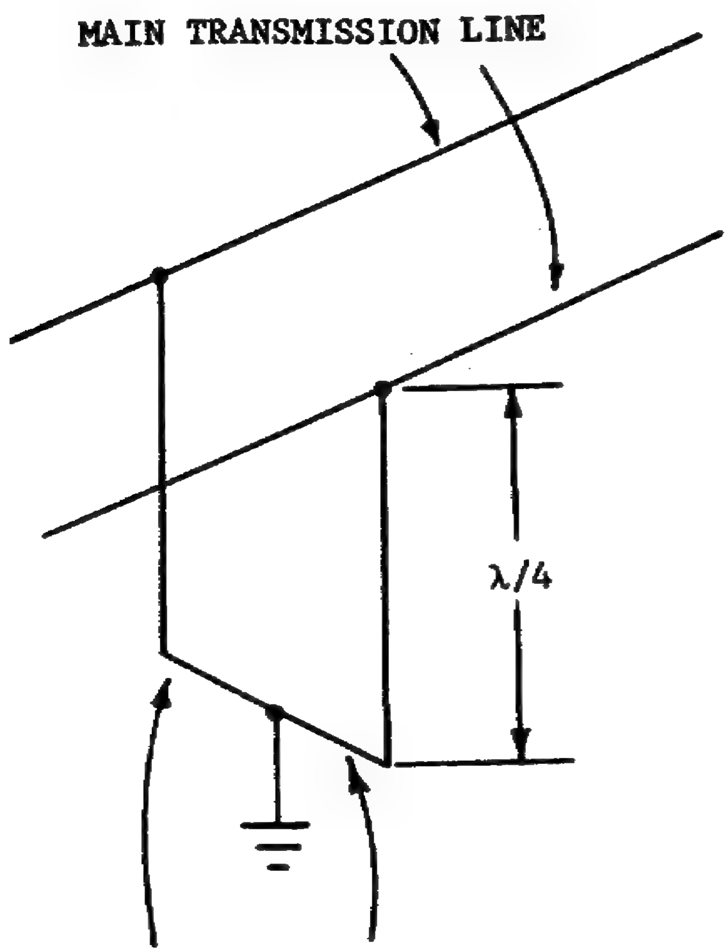
a. parallel-resonant circuit.

b. series-resonant circuit.

c. capacitor.

d. resistor.

Figure 43. Quarter-Wave Section Transmission Line.



10. Assume that the second harmonic is present on the transmission line shown in Figure 43. The shorted quarter-wave stub presents an impedance to the second harmonic that will resemble the impedance offered by the circuit shown in Figure 44 in the sketch labeled

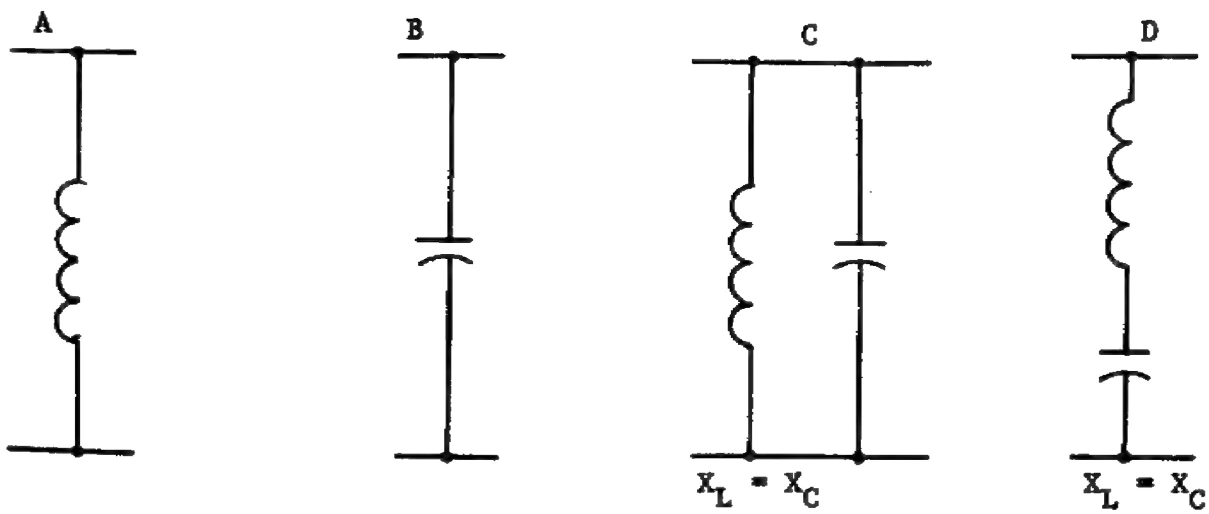
a. A.

b. B.

c. C.

d. D.

Figure 44. Shorted Quarter-Wave Stub Impedance.



11. Assume that the artificial transmission line (ATL) shown in Figure 45 is to be used as a delay line in a radar indicator. This artificial line is composed of

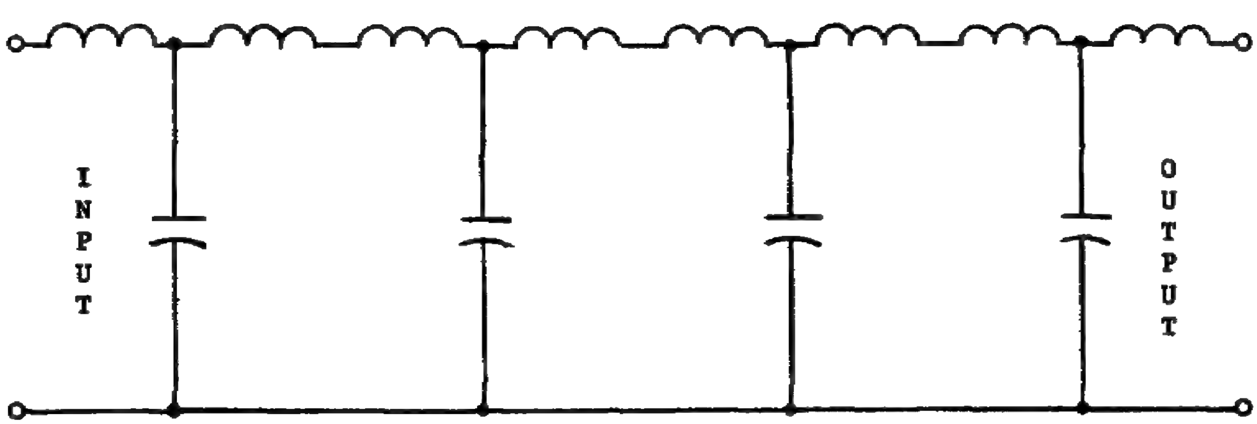
a. four "T" sections.

b. four "L" sections.

c. two "pi" sections.

d. one "L" section and three "T" sections.

Figure 45. Sections of an ATL.



12. If a real transmission line has a capacitance of 10 picofarads per meter and an inductance of 0.4 microhenries per meter, it will delay a voltage pulse 4 microseconds if its length is

a. 1,000 meters.

b. 2,000 meters.

c. 10,000 meters.

d. 20,000 meters.

13. Assume that the ATL shown in Figure 46 is to be used to form the rectangular pulse that controls the magnetron in a radar transmitter. The characteristic resistance of this pulse-forming network is

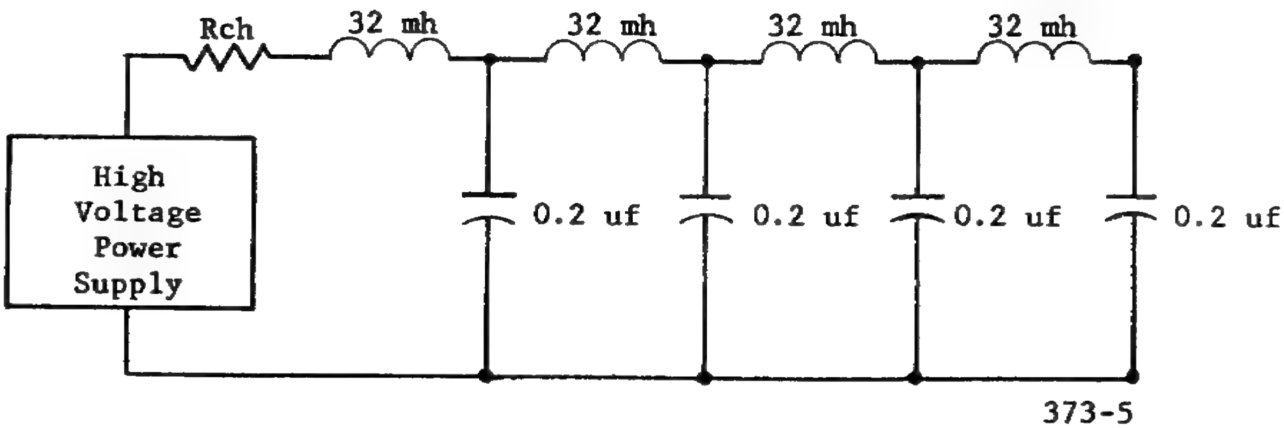
a. 400 ohms.

b. 2,000 ohms.

c. 40,000 ohms.

d. 800,000 ohms.

Figure 46. Pulse-Forming Network.



14. Assume that a rectangular pulse is applied to the ATL shown in Figure 47. What will be the time delay introduced by this ATL?

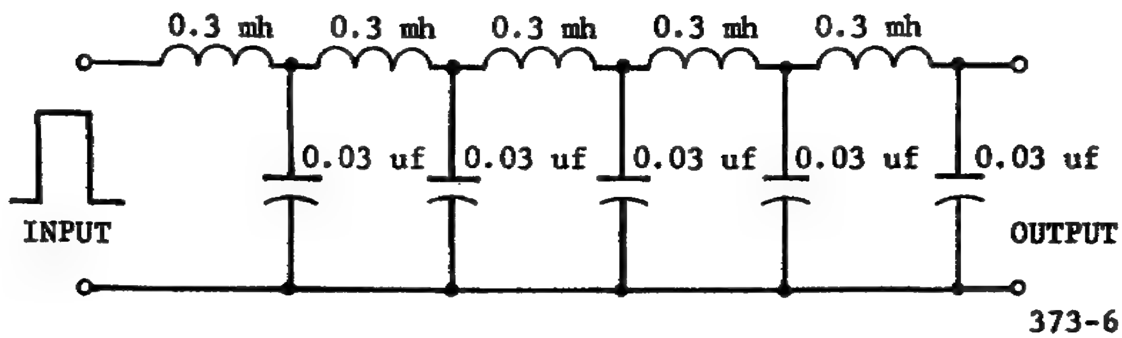
a. 3 microseconds.

b. 9 microseconds.

c. 12 microseconds.

d. 15 microseconds.

Figure 47. Artificial Transmission Line.

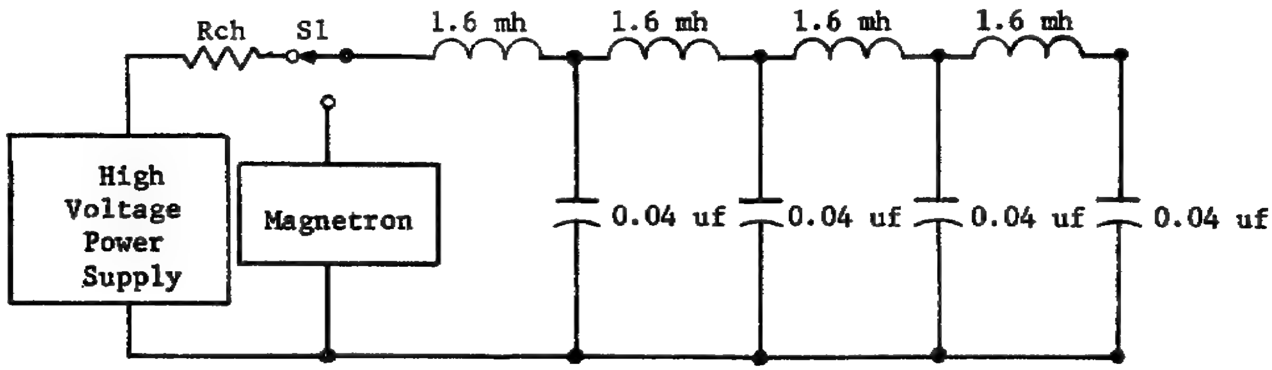


SITUATION

Assume that the ATL shown in Figure 48 is to be used as the pulse-forming line in a radar modulator. Assume that the charging resistance of the high-voltage source is equal to the characteristic resistance of the pulse-forming line.

Exercises 15 and 16 are based on the above situation.

Figure 48. Pulse-Forming Line.



15. The four-section ATL shown in Figure 48 will be fully charged after

    a. 8 microseconds.

    b. 16 microseconds.

    c. 32 microseconds.

    d. 64 microseconds.

16. The charging resistance is designed to be equal to the characteristic resistance of the pulse-forming line shown in Figure 48. What is the value of the charging resistance?

    a. 200 ohms.

    b. 400 ohms.

    c. 600 ohms.

    d. 800 ohms.

17. Six microseconds after switch S1 is closed in the ATL shown in Figure 49, the voltage across the charging resistance will be

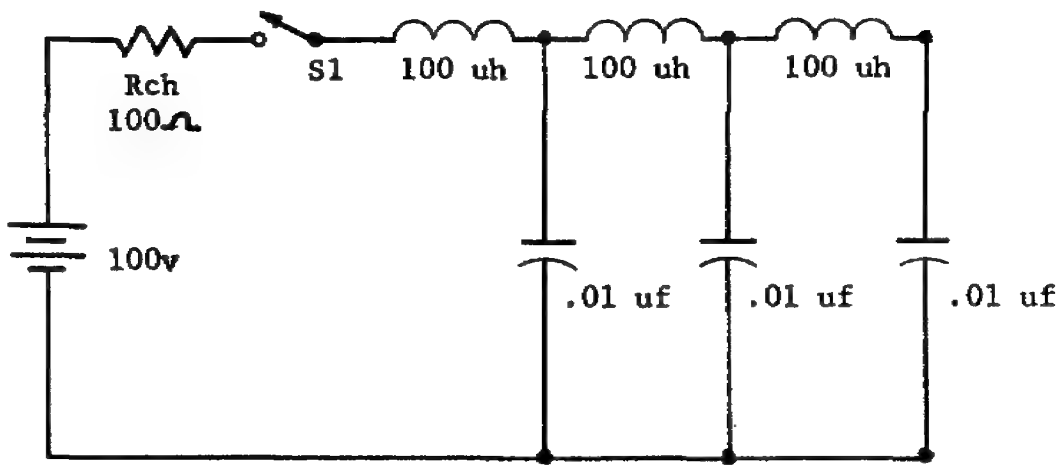
a. equal to zero.

b. equal to the voltage across Rc.

c. greater than the voltage across Rc.

d. one-half the value of the voltage across Rc.

Figure 49. Charging ATL.



18. Assume that the pulse-forming network shown in Figure 50 is being designed to produce a rectangular output pulse. To produce the desired pulse, the circuit's applied voltage will be equal to

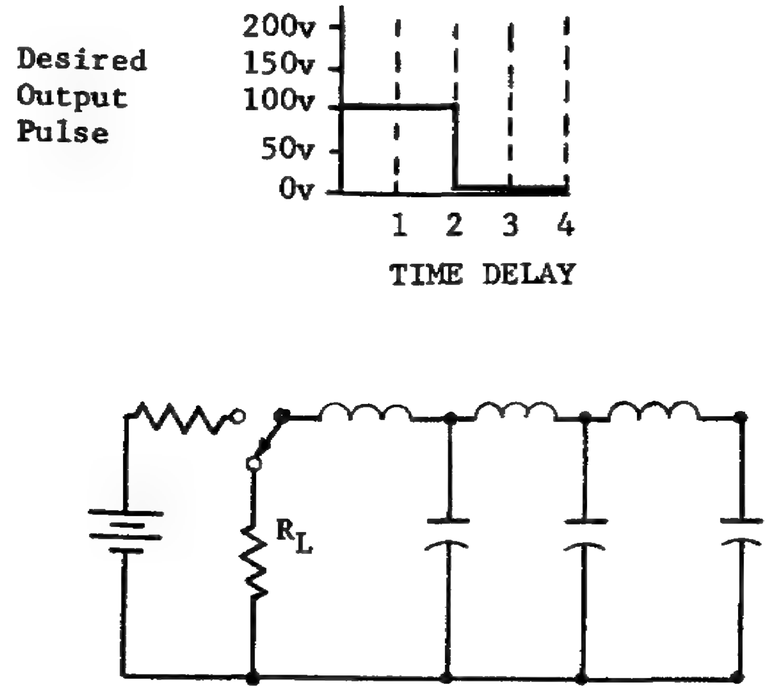
a. 100 volts.

b. 400 volts.

c. 200 volts.

d. 300 volts.

Figure 50. Network to Form Rectangular Pulse.



19. If a pulse-forming network charges and discharges in an exponential pattern, it can be assumed that the circuit's characteristic resistance is

a. greater than the charging resistance and less than the load resistance.

b. less than the charging resistance and greater than the load resistance.

c. greater than the charging resistance and load resistance.

d. less than the charging resistance and load resistance.

20. Assume that the waveforms shown in Figure 51 are the charge and discharge waveforms across a pulse-forming network. By analyzing the waveforms, it can be determined that the pulse-forming network's characteristic resistance is

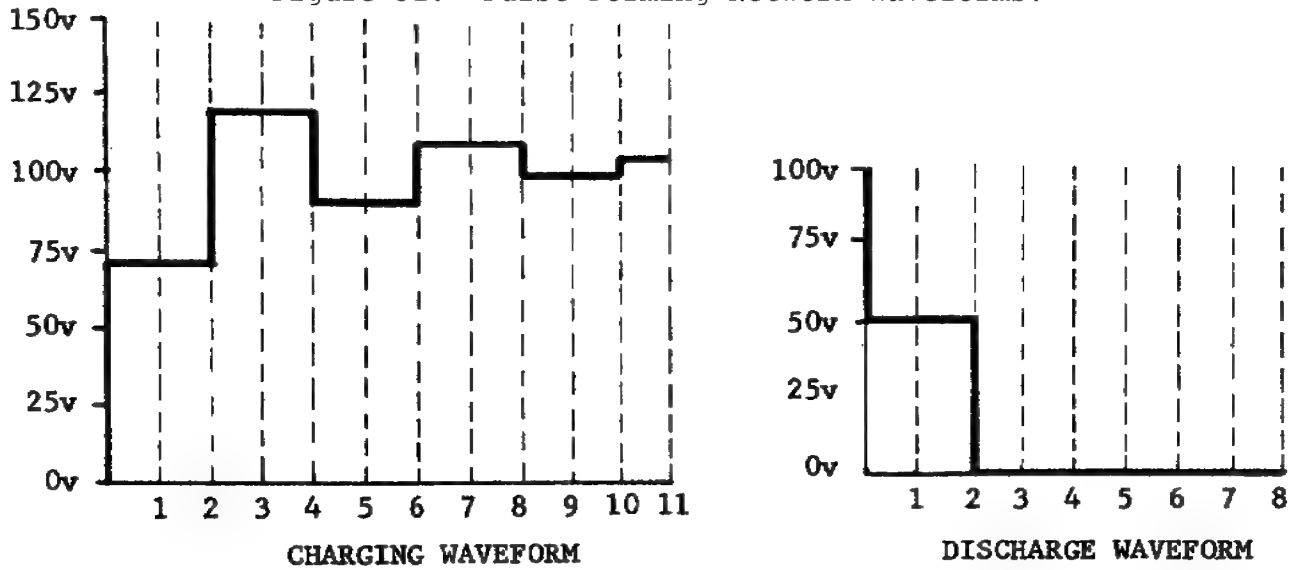
a. equal to the charging resistance and load resistance.

b. less than the charging resistance and equal to the load resistance.

c. equal to the charging resistance and greater than the load resistance.

d. greater than the charging resistance and equal to the load resistance.

Figure 51. Pulse-Forming Network Waveforms.



Check your answers with lesson 1 solution sheet.

LESSON TWO

HIGH-LEVEL MODULATION

TASK

Describe the functions performed by the components in a high-level modulator circuit, differentiate between conventional and hydrogen thyratron circuits, differentiate between conventional and hydrogen thyratron circuit operations, determine the width and amplitude of the pulse applied to the magnetron in a high level modulator circuit, and differentiate between conventional transformers and pulse transformers.

CONDITION

(Performance-Oriented) Given this subcourse, pencil, and paper.

STANDARD

(Performance-Oriented) Demonstrate competency of task skills and knowledge by correctly responding to 75 percent of the multiple-choice test covering radar transmitters.

REFERENCES

FM 11-63

Learning Event 1:
BASIC RADAR TRANSMITTER

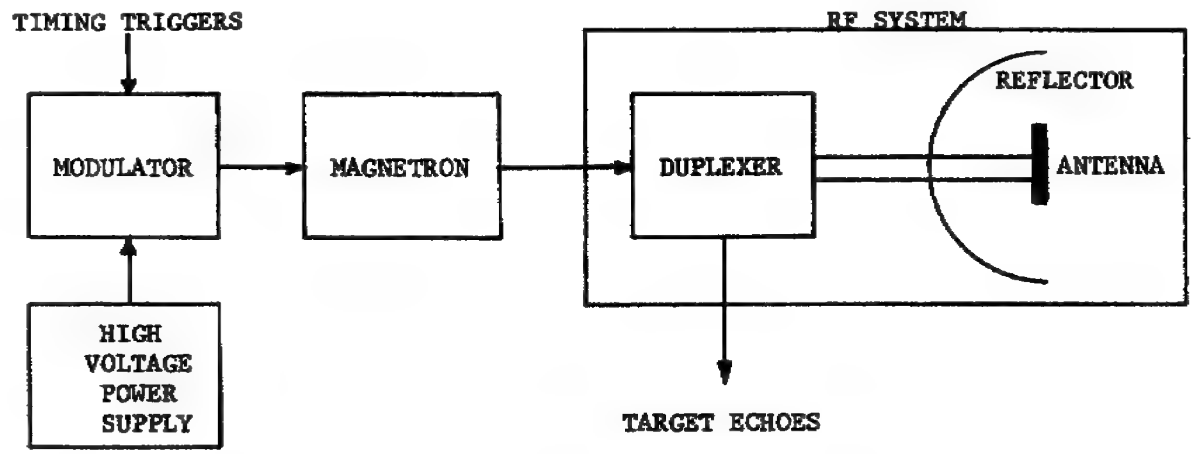
1. General.

Although all components, such as the transmitter, receiver, timer, and indicator are equally responsible for the efficient operation of a radar set, much of the effectiveness of a radar set depends upon the transmitter. The transmitter generates RF energy in short powerful bursts of sufficient strength to reach all targets within the maximum range of the radar set.

2. Basic transmitter system.

The major components of a radar transmitter are shown in Figure 52. The components are the high-voltage power supply, modulator, and magnetron. The RF system, duplexer, and antenna are additional components needed to send the RF energy into space and to receive the target echoes.

Figure 52. Basic Radar Transmitter.



(1) High-voltage power supply. The high-voltage power supply is used to charge the pulse-forming line in the modulator. Switches, relays, and interlocks are used in conjunction with the power supply to control the application of voltages, prevent overloads from damaging components, and to protect personnel from the high voltages.

(2) Modulator. The modulator controls the operation of the magnetron by supplying it with the high-voltage rectangular pulses of DC. In effect, the modulator acts as the power supply for the magnetron. When the modulator output is applied to the magnetron, the magnetron oscillates. When the pulse is removed, the magnetron stops oscillating. The modulator acts like a switch that turns the magnetron on and off.

(3) Magnetron. The magnetron is really the heart of the transmitter because it is a high-power, high-frequency oscillator that produces bursts of RF energy for short periods of time. The time that the magnetron is on is very short as compared to the time that it is not oscillating. When the magnetron is pulsed, it generates short bursts of RF energy. The frequency at which the magnetron is pulsed, that is, turned on and off, is known as the pulse repetition frequency (PRF) and the frequency at which the magnetron oscillates is known as the carrier frequency.

(4) RF system. The RF system consists of transmission lines that carry the RF energy to the antenna with a minimum loss of power. The transmission lines also carry the echo from the antenna to the receiver. Waveguides are usually used in preference to coaxial cables because of their greater efficiency and lower losses.

(5) Duplexer. The duplexer, or TR switch, makes it possible for the radar to use the same antenna for both transmitting and receiving. When the modulator pulses the magnetron, the TR switch connects the antenna to the transmitter and disconnects the receiver. This protects the receiver because it prevents the full power of the magnetron from reaching the receiver. Then, as soon as the transmitter goes off, the TR switch connects the antenna to the receiver and disconnects the transmitter. This allows the echoes reflected from targets to go only to the receiver. The TR switch is a high speed switch that works automatically.

(6) Antenna. The antenna takes the RF energy from the transmission line and sends it into space. The antenna also picks up the return echoes. The radar antenna is made very directional by using reflectors to concentrate the RF energy into the desired beam pattern. Various types of antennas are used in radar and the type used depends upon the function of the radar system.

Learning Event 2:
HIGH-LEVEL MODULATION

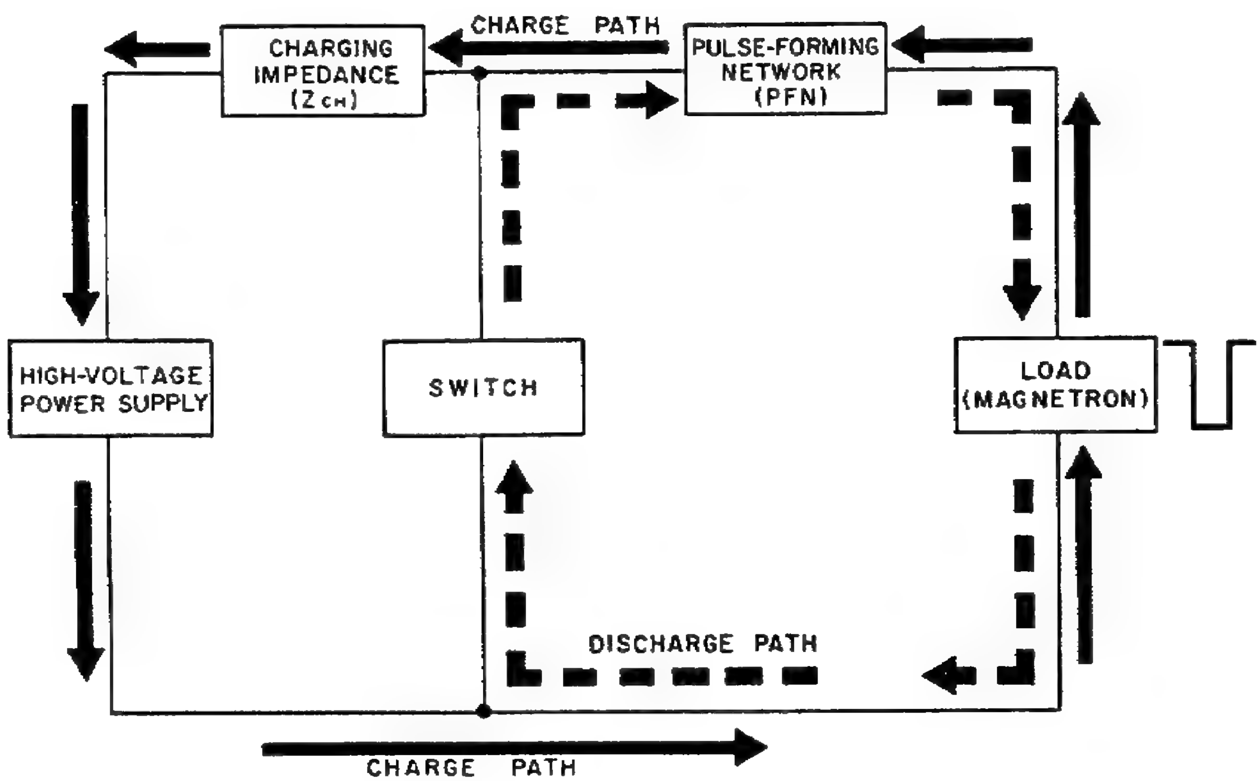
1. General.

a. Most radars today use a pulse modulation system in which a magnetron, under the control of the modulator, generates short, regularly-spaced bursts (pulses) of RF energy. The modulator controls the magnetron with high-voltage, rectangular DC pulses. The accuracy of the radar depends on the shape of the pulse developed by the modulator. You learned that the modulating pulse must have a constant amplitude to keep the magnetron oscillating at its correct frequency, and it must also have steep sides to ensure accurate range determination.

b. You also learned that there are two ways to form the modulating pulse: either by low-level modulation or high-level modulation. Although some older radar sets still use low-level modulation, modern radars use the more efficient

and simpler high-level modulation system. The purpose of this lesson, then, is to describe the operation of a high-level modulation system. You will learn how the components in the high-level modulator work together to develop the high-voltage rectangular DC pulse. Finally, you will learn how to maintain and troubleshoot practical high-level modulators.

Figure 53. How High-Level Modulation Works.



c. Look at Figure 53 again. Actually there are two circuits involved in the operation of the modulator: a charge circuit and a discharge circuit. The charge circuit consists of the high-voltage power supply, the charging impedance, the PFN, and the load. The discharge circuit consists of the switch, the load, and the PFN.

d. Now that you have a general idea of how the basic high-level modulator works, the next step is to learn what each component does in the system. Let's start with the pulse-forming network.

Learning Event 3:
THE PFN

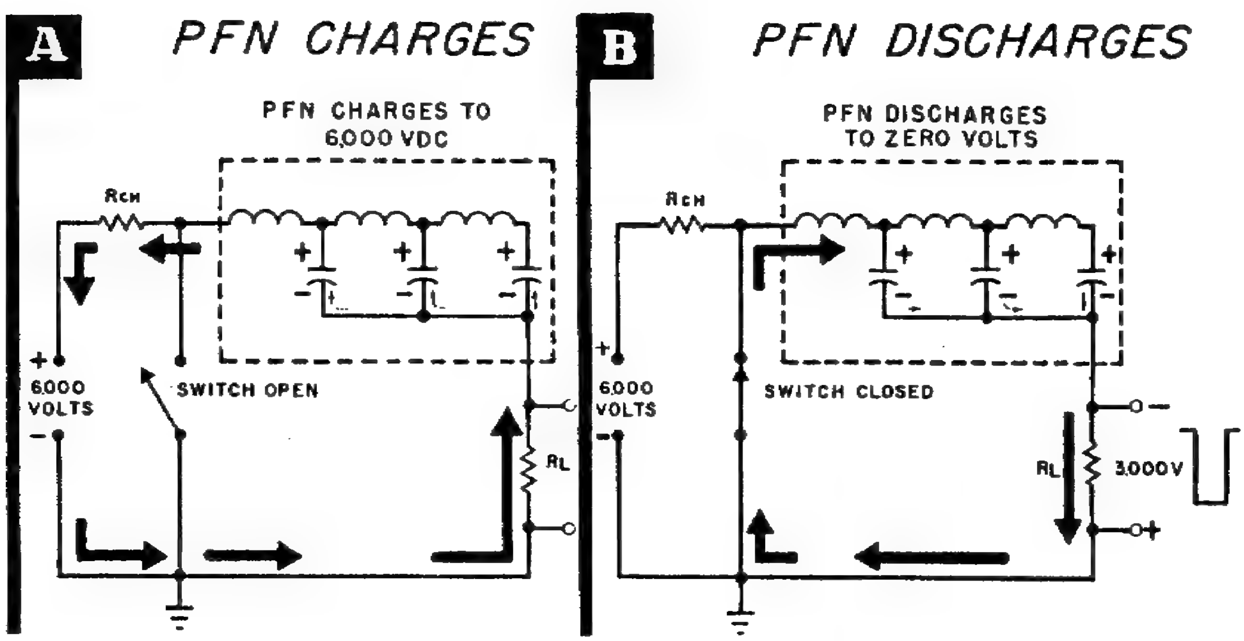
1. Figure 54 shows that the PFN is an ATL. Recall from a previous lesson, Artificial Transmission Lines, that one of the major uses of ATL is to form radar pulses. You learned that the ATL determines the pulse width and shape. At this time, you should review the previous lesson concerning basic principles of ATL. Note carefully those sections dealing with the following:

a. The charge of an ATL through a source resistance (Rch) greater than the characteristic resistance (Rc) of the ATL.

b. The discharge of an ATL through a load resistance (RL) equal to the characteristic resistance of the ATL.

2. Now look at Figure 54 again. Part A shows a simplified schematic of the charging circuit of the modulator. The high-voltage power supply charges the PFN to 6,000 volts DC through the charging impedance. In this case, the charging impedance is a resistor, called the charging resistance Rch. The characteristic resistance (Rc) of the line is less than the source and charging resistances. Therefore, the PFN charges exponentially to the source voltage of 6,000 volts DC. No pulse is formed across the load during the charge cycle because the impedance of the load (magnetron and its pulse transformer) is very low and the charge time is very long.

Figure 54. Charge and Discharge of the PFN.

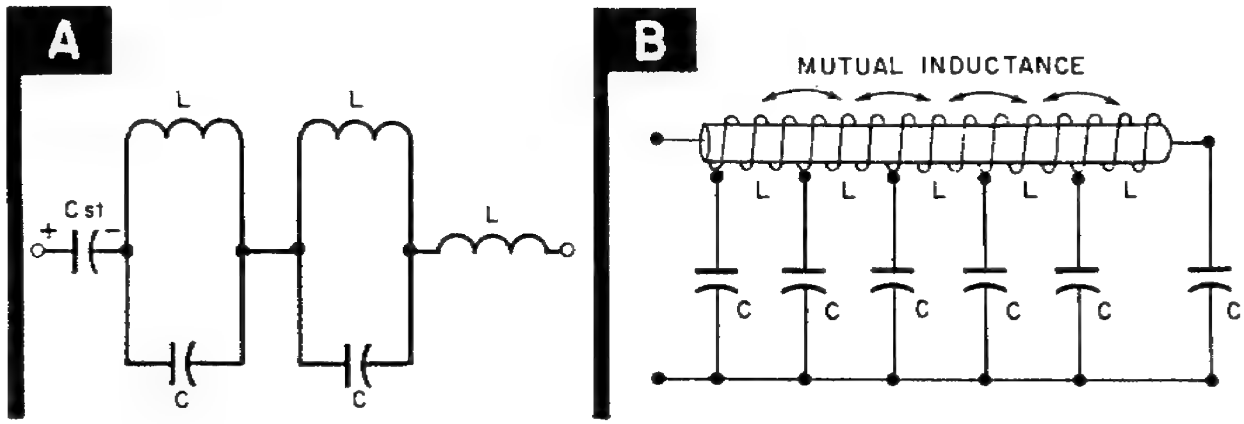


3. Part B of Figure 54 shows the discharge cycle. The closed switch becomes a short-circuit across the PFN. Therefore, the PFN discharges rapidly through the load, forming a rectangular pulse. The reason the pulse is rectangular is that the PFN discharges through a load resistance equal to the characteristic resistance of the line. Thus, the pulse amplitude is 3,000 volts DC, half the voltage to which the PFN is charged. The pulse width is equal to two TDs.

4. So you see, the rectangular pulse used to trigger the magnetron into oscillation is actually formed during the discharge of the PFN and at a high power level. Because of the high voltage at which it must operate, a conventional ATL cannot be used. The capacitors in the line would have to be very large to withstand the high voltage. So, a specially-constructed ATL is used, called a Guillemin line.

5. Figure 55 shows the schematics of two types of Guillemin lines used frequently in radar modulators. The network in Part A simulates the characteristics of an open-end transmission line. Notice that the coils and capacitors in the individual sections are in parallel. A single capacitor, Cst, stores the entire high-voltage charge. The L-C circuits develop oscillatory voltages which add to the voltage of the storage capacitor Cst during the discharge cycle. The oscillatory voltages make the network voltage fall to zero in two equal steps.

Figure 55. Two Types of Guillemin Lines
Used as Pulse-Forming Networks.



6. Part B of Figure 55 shows an open-end artificial transmission line with magnetic coupling between the coils. Mutual inductance is used to remove undesirable oscillations on the top of the pulse. Notice that the line is actually a long solenoid with tap points for equal-value capacitors. The combination of all capacitors in parallel makes up the storage capacitor. This type of PFN is the one used most frequently in modern radar systems.

7. Pulse-forming networks are usually "potted," sealed in an oil-filled metal container. The oil is used for compact high voltage insulation. You can see, then, that there is no maintenance to be done on the PFN. If one of the elements of the line fails, you must replace the entire line.

8. Brief review.

a. Most modern radar sets use the high-level modulation system in which the pulse is formed at a high power level.

b. In high-level modulation, the pulse is formed by discharging a pulse-forming line through a load resistance equal to the characteristic resistance of the line.

c. The PFN determines the shape and width of the pulse.

d. The amplitude of the pulse is equal to one-half the voltage to which the line is charged.

e. The pulse width is equal to two TDs.

f. The PFN is discharged at the pulse repetition frequency of the radar.

g. A Guillemin line is a specially-constructed, pulse-forming network.

Learning Event 4:
HYDROGEN THYRATRON SWITCH

1. The switch used to discharge the PFN is one of the most critical components in the high-level modulator. Here are some reasons why.

a. The switch must be nonconducting (off) during the charge of the pulse-forming network.

b. The switch must close very rapidly at the pulse repetition frequency of the radar.

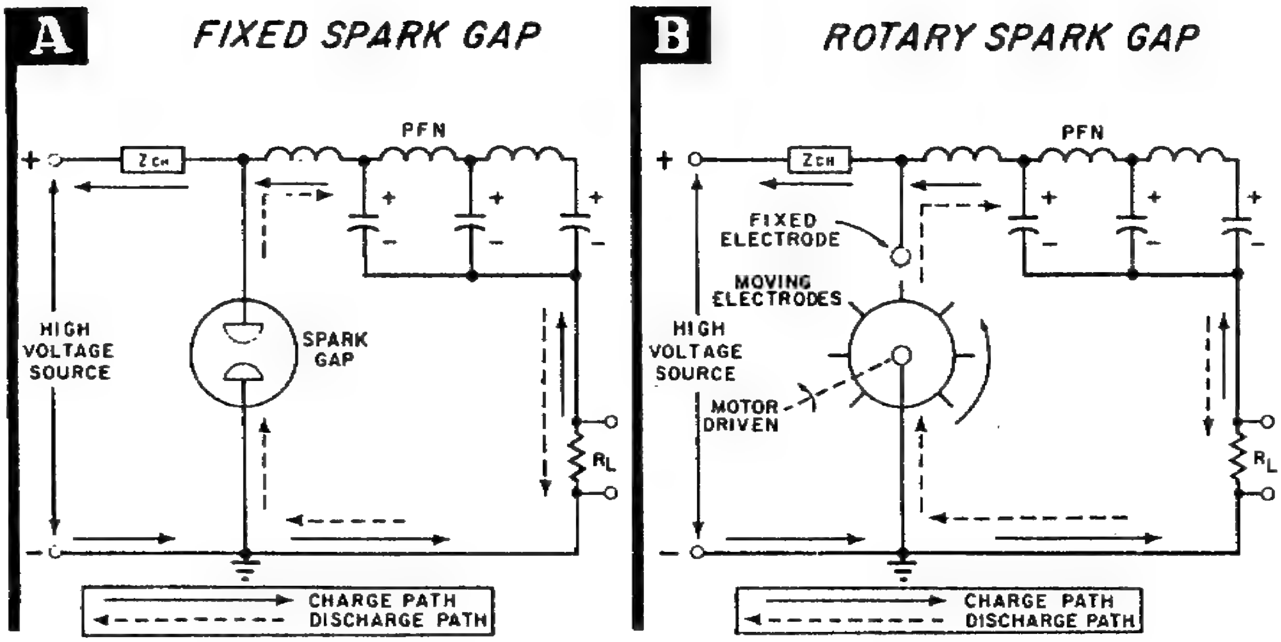
c. The switch resistance must be as small as possible during the discharge of the PFN.

d. The switch must be capable of conducting high currents without damage.

e. Some early radar sets used spark gaps to discharge the PFN. Figure 56 shows two common types: a fixed spark gap and a rotary spark gap.

(1) The two-electrode spark gap shown in Part A works just like the spark plug in your car. During the charge of the PFN, the spark gap is an open circuit. Hence, its resistance is very large. As the PFN charges, the potential across the electrodes builds up rapidly. When the potential is large enough, the air between the electrodes breaks down (ionizes) and a spark jumps across the electrodes. This makes the resistance of the spark gap very small, and, thus, the PFN is short-circuited.

Figure 56. Early Radar Sets Used Spark Gaps to Discharge the PFN.



(2) The rotary spark gap shown in Part B of Figure 56 consists of a set of moving electrodes rotating in front of one or more fixed electrodes. The disk carrying the moving electrodes is mounted directly on the shaft of the driving motor. As the disk rotates, one of the moving electrodes approaches the fixed electrode. The air between the two electrodes starts to ionize. A spark occurs and the PFN discharges through the very low resistance of the spark gap. By the time the next moving electrode approaches the fixed electrode, the pulse-forming recharged network will have been recharged.

(3) Although it is simple and can handle large amounts of power, the spark gap, nevertheless, has some serious disadvantages:

(a) The spark gap cannot be used at high pulse repetition frequencies.

(b) It is unstable, that is, the firing time is uncertain.

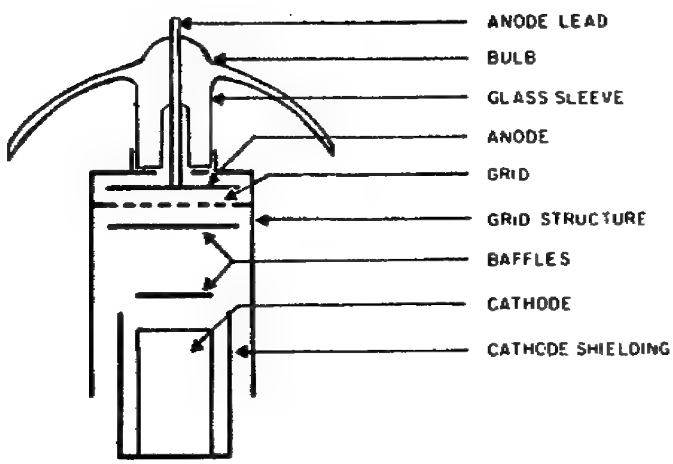
(c) The electrodes become pitted and corroded quite easily.

(4) Therefore, instead of the spark gap, modern radar sets use the HYDROGEN THYRATRON as an electronic switch because it is small, light, and highly efficient. The THYRATRON can be triggered accurately by low-voltage pulses on the grid, and it can operate over a wide range of plate voltages.

2. The HYDROGEN THYRATRON.

a. Figure 57 shows the internal structure of a type 5C22 HYDROGEN THYRATRON. First, look at the anode lead. Notice that it is enclosed in a glass sleeve to prevent interaction between the anode-lead wire and the outside of the grid structure. Note, too, that the grid structure completely surrounds the anode. This keeps the perpendicular distance between grid and anode constant.

Figure 57. Construction of 5C22 thyratron.

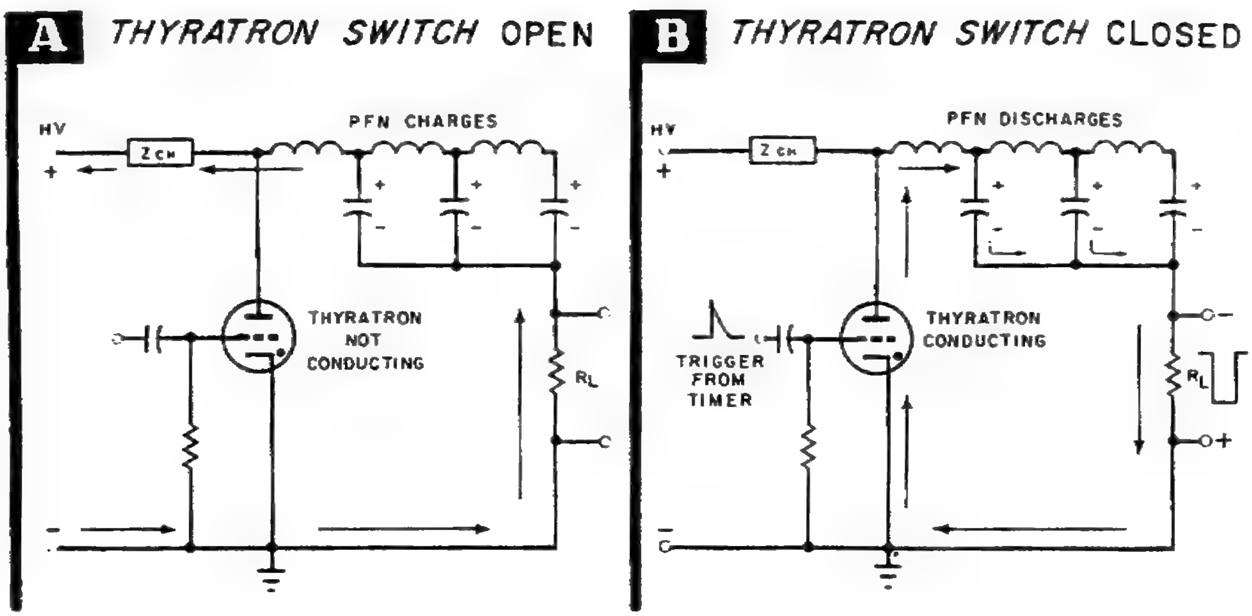


b. HYDROGEN THYRATRONS differ from the more common thyratron types you studied in that the HYDROGEN THYRATRON has a positive control-grid characteristic. This means the tube won't ionize with zero bias. Instead, it must be triggered by a positive voltage high enough to draw grid current. To have a positive control-grid characteristic, the cathode is completely shielded from the anode (Figure 57). Besides the cathode-shield structure, there are two baffles just below the perforated grid section located between the cathode and anode. These baffles prevent the anode field from extending into the cathode region and affecting the electrons emitted from the cathode.

3. The THYRATRON as a switch.

a. Figure 58 shows a HYDROGEN THYRATRON used as a switch in a high-level modulator. In Part A, the hydrogen thyratron is nonconducting as the PFN charges to the source voltage. At the instant the PFN reaches its maximum charge, a positive trigger from the timer unit comes in on the grid of the THYRATRON (Part B of Figure 58). To start conduction, the trigger must be at least 150 volts. The positive trigger causes grid current to flow, which produces electrons and ions outside the cathode-shield structure. Some of these electrons and ions reach the baffles just below the grid: When the number of electrons and ions in this area is large enough, the anode produces ionization and causes the tube to conduct heavily.

Figure 58. The HYDROGEN THYRATRON is an Electronic Switch.



b. The HYDROGEN THYRATRON now acts as a closed switch in Part B of Figure 58. The PFN discharges quickly through the conducting tube and produces a rectangular pulse across the load. As the PFN discharges, the plate voltage of the THYRATRON falls rapidly until the tube deionizes. Then the tube becomes an open switch again.

c. Perhaps at this time, you are wondering why hydrogen gas is used instead of some other gas, such as argon or mercury vapor. Hydrogen gas is used because it has a short deionization time compared to the other gases. Also hydrogen allows high currents to pass through the tube without causing damage to the cathode.

4. Brief review.

a. The switch discharges the pulse-forming network at the pulse-repetition frequency of the radar.

b. Early radar sets used fixed and rotary spark gaps as switches to discharge the pulse-forming network.

c. Modern radar sets use the HYDROGEN THYRATRON as an electronic switch.

d. The HYDROGEN THYRATRON is small, light, and highly efficient. Also, it can be triggered accurately.

e. The HYDROGEN THYRATRON has a positive control-grid characteristic. Grid current must flow first before the tube will ionize.

f. Hydrogen gas is used because it will deionize quickly and allow high current flow without damage to the cathode.

Learning Event 5:
CHARGING IMPEDANCE

1. Charging impedance isolates the high-voltage power supply from the closed switch while the PFN is discharging. In other words, the charging impedance prevents the closed switch from short-circuiting the source voltage. Isolation, then, is one of the primary purposes of the charging impedance. However, the charging impedance has another important use, that of increasing the amplitude of the modulator pulse.

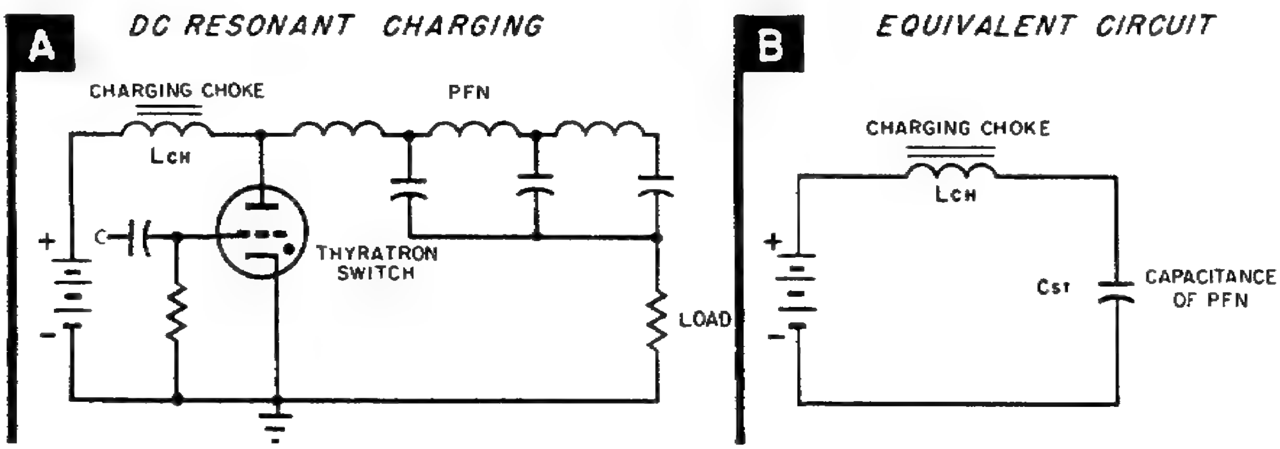
a. For example, recall that the amplitude of the pulse developed across the load is equal to half the voltage to which the PFN was charged. This means that if the PFN charges to 6,000 volts, then, upon discharging, the PFN will develop a 3,000-volt pulse across the load. Suppose, however, a pulse of 6,000 volts is needed across the load. One way of getting the additional voltage is to use a 12,000-volt power supply. The PFN, then, charges to 12,000 volts and, upon discharging, the PFN develops a 6,000-volt pulse across the load. However, this method is costly and inefficient.

b. A simpler and highly efficient method uses an inductor as a charging impedance. This method, called DC resonant charging, allows the PFN to charge to a voltage nearly double that of the power supply. Thus, with a source voltage of 6,000 volts, the PFN can charge to 12,000 volts. The extra 6,000 volts is supplied by the inductor. When the PFN discharges now, it develops a 6,000-volt pulse across the load.

2. DC resonant charging circuit.

a. Part A of Figure 59 shows a simplified DC resonant charging circuit. Notice the charging inductance, Lch, called a charging choke, in series with the DC source voltage and the PFN. The reason the circuit is called DC resonant charging is that, first of all, the PFN is charged by a DC source and, second, the inductance of the choke, Lch, resonates with the capacitance of the PFN. The equivalent circuit of this simple series resonant circuit is shown in Part B of Figure 59. In the equivalent circuit, the PFN is represented by a single storage capacitor, Cst. The inductance of the load (pulse transformer and magnetron) can be neglected because its effect is small compared to that of the choke, Lch.

Figure 59. The DC Resonant Charging Circuit.



b. The equivalent circuit is used in Figure 60 to simplify the explanation of the DC resonant charging circuit. Keep in mind that Cst represents the pulse-forming network. You will learn about the charging cycle

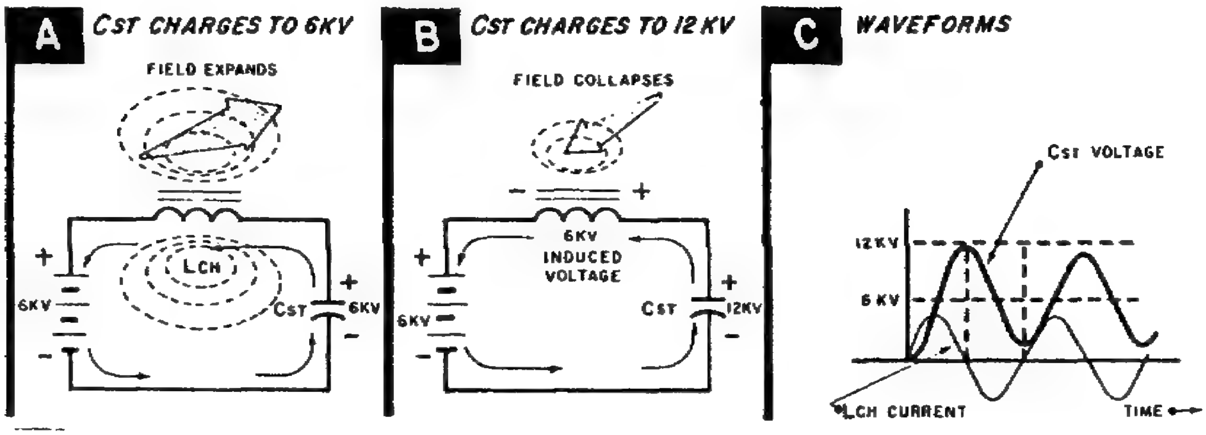
first and, then, the discharge cycle. Before starting, assume a pulse has just been developed across the load. Hence, storage capacitor Cst is fully discharged. Also, there is no current flowing through charging choke Lch.

c. At the start of the charging cycle, storage capacitor Cst begins to charge to the 6KV (6,000-volt) source. Current flow through the choke in Part A of Figure 61 sets up a magnetic field. The charge cycle is slow at first because of the opposing effect of the choke. Remember, a coil produces an induced voltage which opposes changes in current flow. Since current is increasing, the induced voltage produced by the expanding magnetic field opposes the supply voltage.

d. Now, as Cst reaches its initial charge of 6KV, current flow starts to drop off, causing the magnetic field of the choke to collapse. Once again, the self-inductance of the choke opposes this change in current flow. The collapsing magnetic field produces an induced voltage which keeps current flowing in the same direction as before. Part B of Figure 60 shows that this induced voltage, which is 6KV, is in series with the power supply, and so aids the charging current. Notice, now that 12KV is applied to the storage capacitor instead of the 6KV at the start of the cycle. Therefore, Cst charges to 12KV or double the voltage of the source.

e. Part C of Figure 60 shows what happens in the circuit if the switch never closes. Cst won't stay charged because Lch and Cst form a resonant circuit. Therefore, capacitor voltage and inductor current vary sinusoidally as shown in Part C. Notice that capacitor voltage is maximum when inductor current is zero. (See dotted vertical lines in Part C.) This means that the induced voltage of Lch is maximum when inductor current is zero. Recall that the amount of induced voltage depends not only on the size of the inductor, but also on how fast the current is changing. And, current changes fastest when it is going through zero. So Cst charges to twice the source voltage because of the additional induced voltage in series with the source voltage.

Figure 60. How Cst Charges to Twice the Source Voltage.

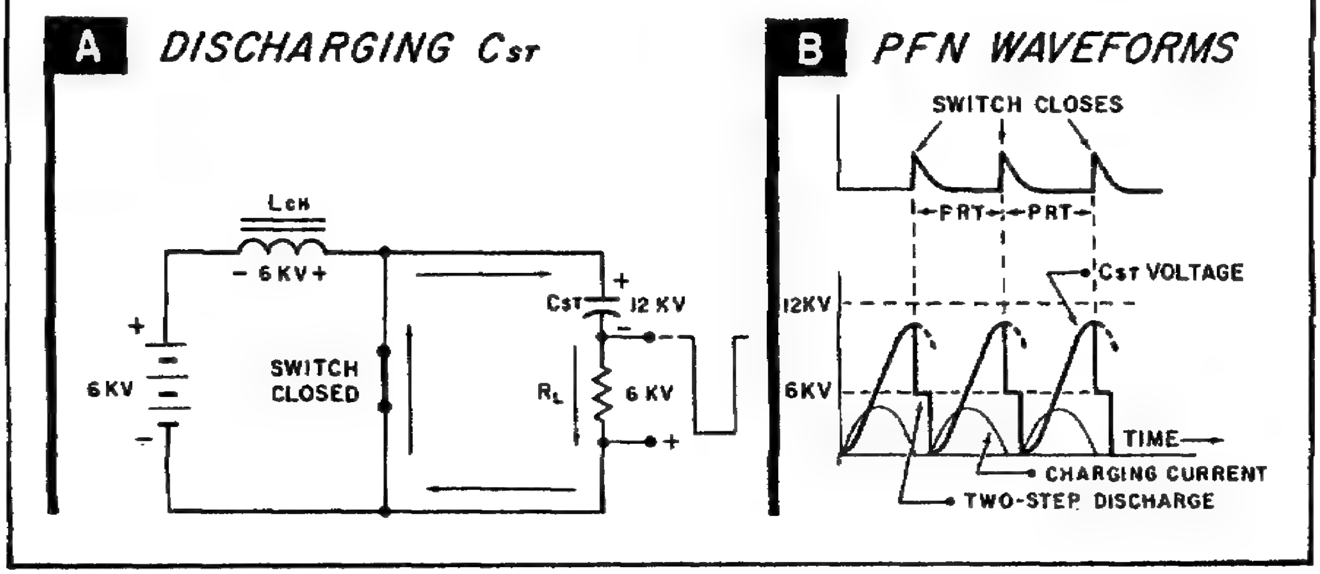


3. Discharge cycle.

a. At the instant the switch closed, the voltage across Cst drops to half the voltage to which it has been charged, 6,000 volts. After two TDs, the voltage across Cst drops to zero. Part A of Figure 61 shows the rectangular pulse developed across the load. At the first instant of time (when the switch closes), the load voltage goes from zero volts to minus 6KV. The pulse remains constant at minus 6KV for two TDs. Then, it falls to zero again. This pulse, as you know, goes to the magnetron.

b. Part B of Figure 61 shows that to get maximum voltage across Cst, the switch must be timed to fire at the peak of the voltage oscillation. The time the switch fires is represented by positive triggers in Part B. Directly below these triggers are the voltage and current oscillations. Notice that when Cst voltage is maximum, the switch closes, causing Cst to discharge in two steps to zero volts. Then, Cst charges again to twice the source voltage. At the peak of the voltage oscillation, the switch closes again, discharging Cst.

Figure 61. The Discharge Cycle.



c. To get the largest pulse possible across the load, then, the switch must close when there is maximum voltage across Cst. This means that the inductance (Lch) of the charging choke and the capacitance (Cst) of the PFN must resonate at one-half the frequency of the PRF. This also means that the radar set can operate at only one PRF which is dependent on the values of Lch and Cst. However, by adding a diode, called a charging diode, in series with the charging choke and the PFN, the pulse repetition frequency can be changed. Let's see how this is done.

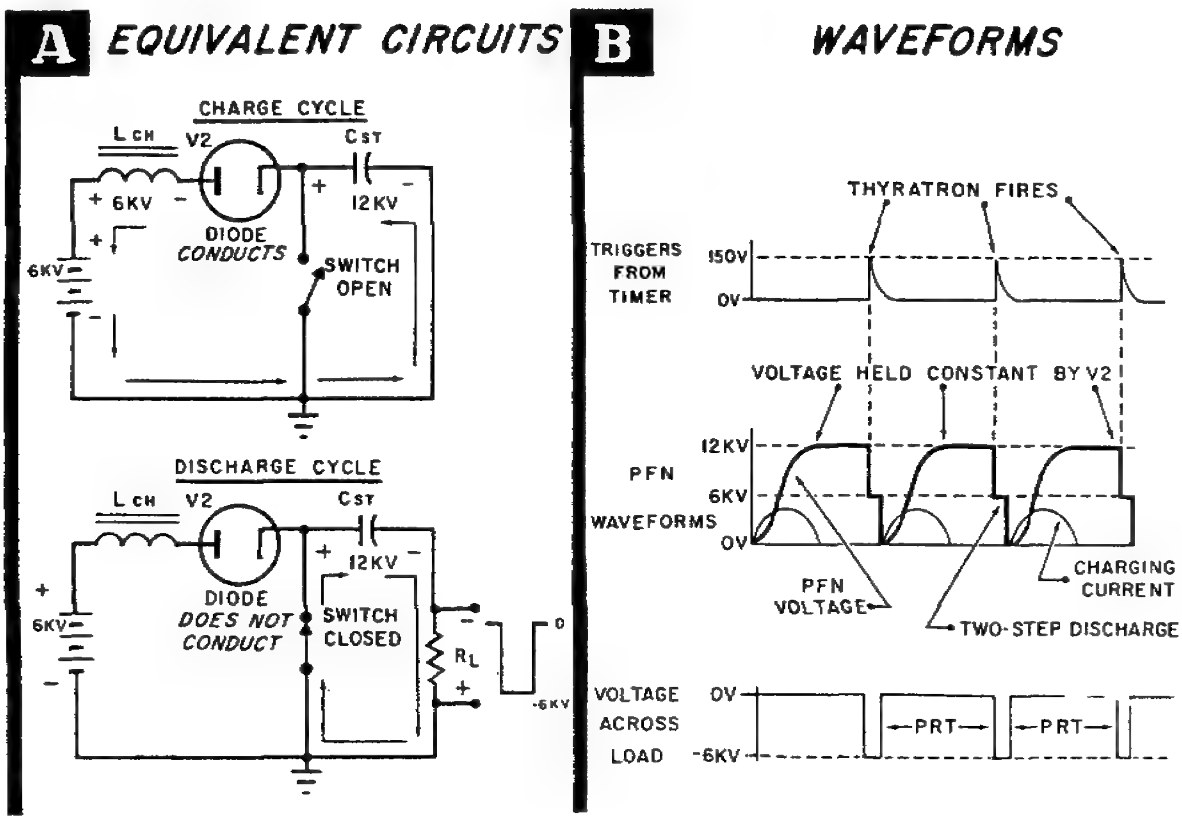
4. Charging diode prevents discharge of PFN.

a. Figure 62 shows the operation of a DC resonant charging circuit with a charging diode in series with Lch and Cst. Part A shows the equivalent circuits of the charge and discharge cycles; Part B shows the waveform analysis. Again, keep in mind that Cst represents the pulse-forming network and the switch takes the place of the HYDROGEN THYRATRON. The load in not shown in the charge cycle because its impedance is small compared to that of Lch.

b. Look at the charging cycle in Part A, first. At the instant the switch opens, Cst starts to charge to the source voltage. The plate of charging diode, V2, is positive with respect to its cathode. Therefore, it conducts heavily, charging Cst through choke, Lch. Because the induced voltage of Lch is in series with the source voltage, Cst charges to 12KV. With Cst charged to 12KV, there is no longer a difference of potential across the diode, so it stops conducting. Now, however, Cst cannot discharge because both V2 and the switch are open circuits. Consequently, Cst holds its charge until the switch closes.

c. Now, look at the discharge cycle in Part A. At the instant the switch closes (thyratron fires), Cst is short-circuited through the load. The discharge of Cst develops a negative rectangular pulse of 6KV. Charging choke and nonconducting diode isolate the power supply from the short-circuited switch.

Figure 62. DC Resonant Charging Circuit With Holding Diode.



d. Part B of Figure 62 shows the waveform analysis of the DC resonant charging circuit. Compare these waveforms with those shown in Figure 61. Notice, now, the PFN does not discharge exactly at the instant the voltage oscillation reaches its peak. Instead, the discharge of the PFN is delayed, resulting in a lower PRF. So, you see, the charging diode allows more than one PRF to be used in a radar set. Note, too, in Part B, that every time the switch fires, a negative pulse is developed across the load. This negative pulse is the modulator output which is coupled to the magnetron by a pulse transformer.

5. Brief review.

a. The charging impedance prevents the closed switch from short-circuiting the power supply.

b. Also, the charging impedance increases the amplitude of the modulator output pulse.

c. DC resonant charging uses an inductor, called a charging impedance.

d. The inductor allows the PFN to charge to voltage nearly twice the power supply voltage. A higher voltage across the PFN means a higher voltage developed across the load when the PFN discharges.

e. A charging diode in series with the charging choke and the PFN prevents discharge of the PFN until the switch closes. Hence, the charging diode allows more than one PRF to be used in the radar set.

Learning Event 6:
THE PULSE TRANSFORMER

1. Figure 63 shows that the modulator load consists of the magnetron, V3, and the pulse transformer, T1. The magnetron is described in detail in a later lesson, so there is no need to go into its operation at this time. The pulse transformer, however, is specially designed and constructed to pass high-voltage pulses without changing their shape. To pass pulses without distortion, a pulse transformer has a ferro-magnetic core, is closely coupled, and has few turns in its windings. Hence, it is not like the conventional transformers you studied earlier in the course. Additional uses of the pulse transformer are:

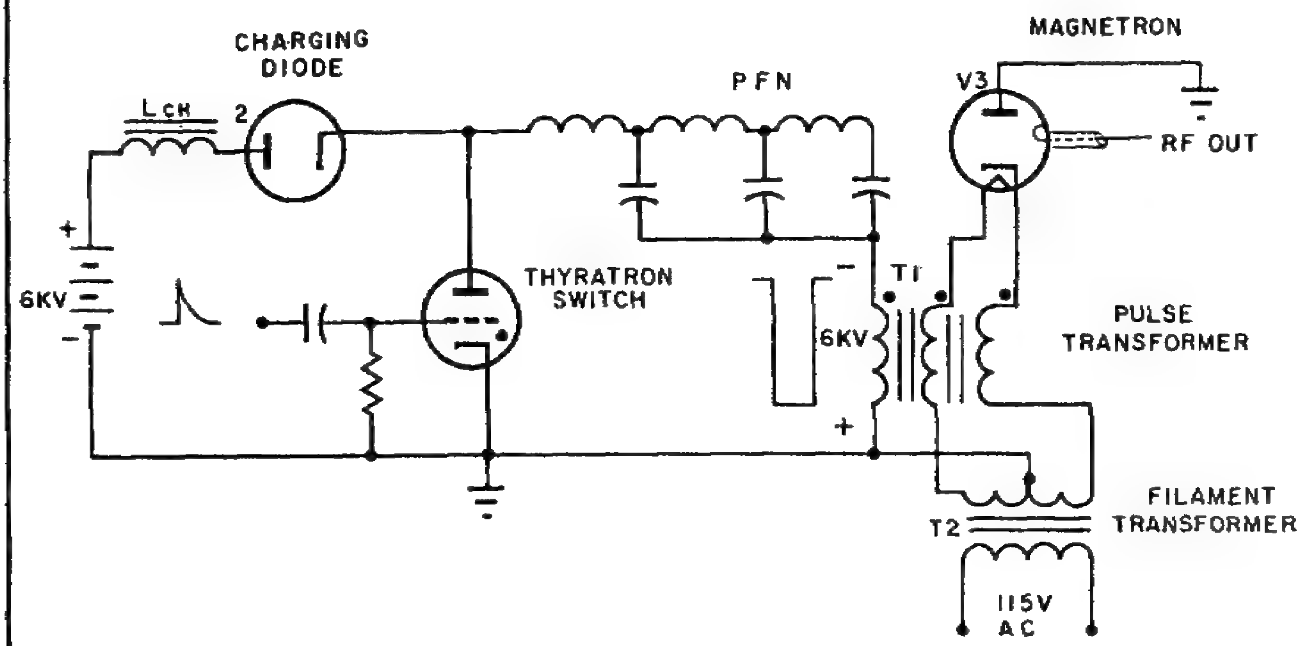
a. It couples the high-voltage modulator pulse to the magnetron with minimum power loss.

b. It matches the low-impedance of the PFN to the high impedance of the magnetron.

c. It steps up the pulse voltage and, thereby, allows the PFN to operate at a much lower voltage than the magnetron.

d. It isolates the magnetron filament transformer from the high pulse voltage.

Figure 63. High-Level Modulator With Pulse Transformer and Magnetron Load.

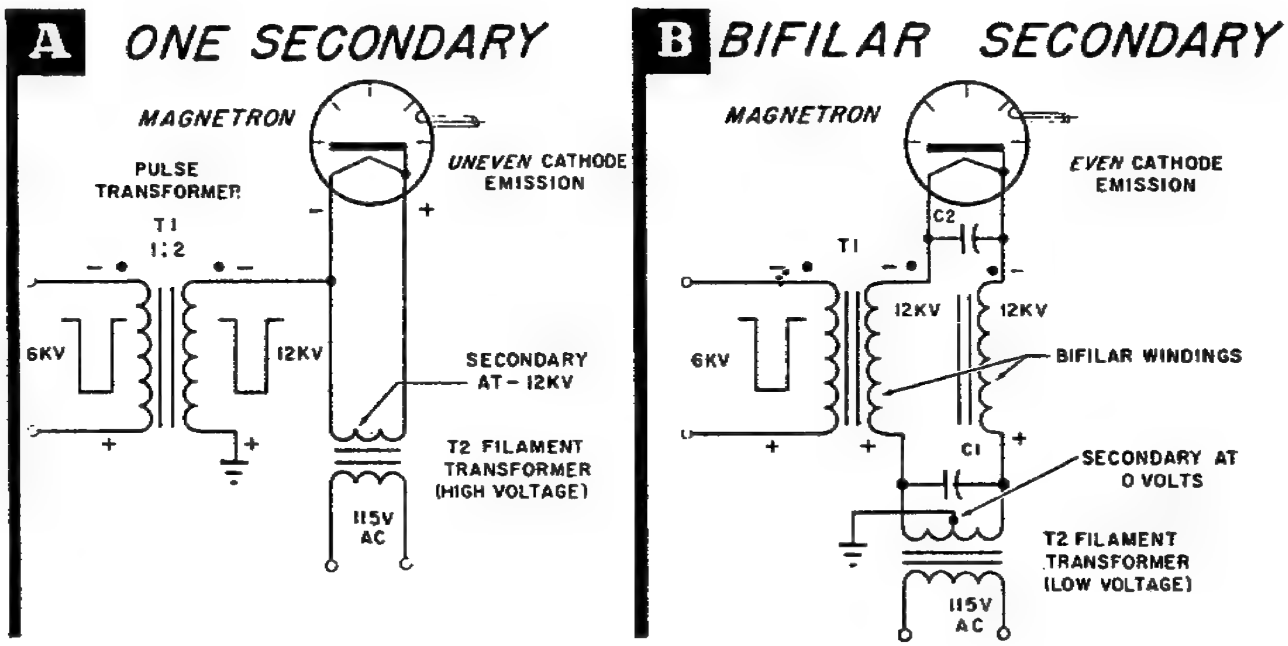


2. Pulse transformer windings.

a. The dots you see on the transformer windings (T1) in Figure 63 indicate points having the same polarity. Thus, if one dot represents a negative polarity, then all the dots are negative. Notice the secondary, connected to the magnetron filament. The secondary is bifilar, that is, the two secondary windings are wound side by side on the core. Wound in this manner, the secondary has exactly the same voltage induced into each winding.

b. Perhaps you are wondering, why use a bifilar secondary when one will do the job? Look at Figure 64 for the answer. Part A of Figure 64 shows a pulse transformer with just one secondary winding. Notice that with a transformer step-up ratio of 1:2, the negative voltage on the magnetron cathode is 12KV. This means that the secondary of the magnetron filament transformer, T2, is a negative 12KV with respect to the primary. To withstand this high voltage, the filament transformer must be heavily insulated, thereby making it bulky and expensive. Another disadvantage of this circuit in Part A is that there is uneven magnetron cathode emission, because there is a difference of potential across the magnetron cathode. One side of the cathode is at minus 12KV; the other side is at a lower potential because of the drop across the cathode itself.

Figure 64. The Pulse Transformer With Bifilar Windings.



c. Compare this to the pulse transformer with a bifilar secondary shown in Part B of Figure 64. Notice that the secondary of the filament transformer is center-tapped and grounded. The high-voltage DC potential across the filament transformer secondary is now zero, with respect to ground, because both ends of the secondary are at the same potential. Therefore, a conventional low-voltage filament transformer can be used. Note, too, that both ends of the magnetron cathode are at the same potential. Capacitors, C1 and C2, ensure that there is no high difference of potential between the two secondary bifilar windings. This prevents uneven cathode emission and thereby stabilizes magnetron operation.

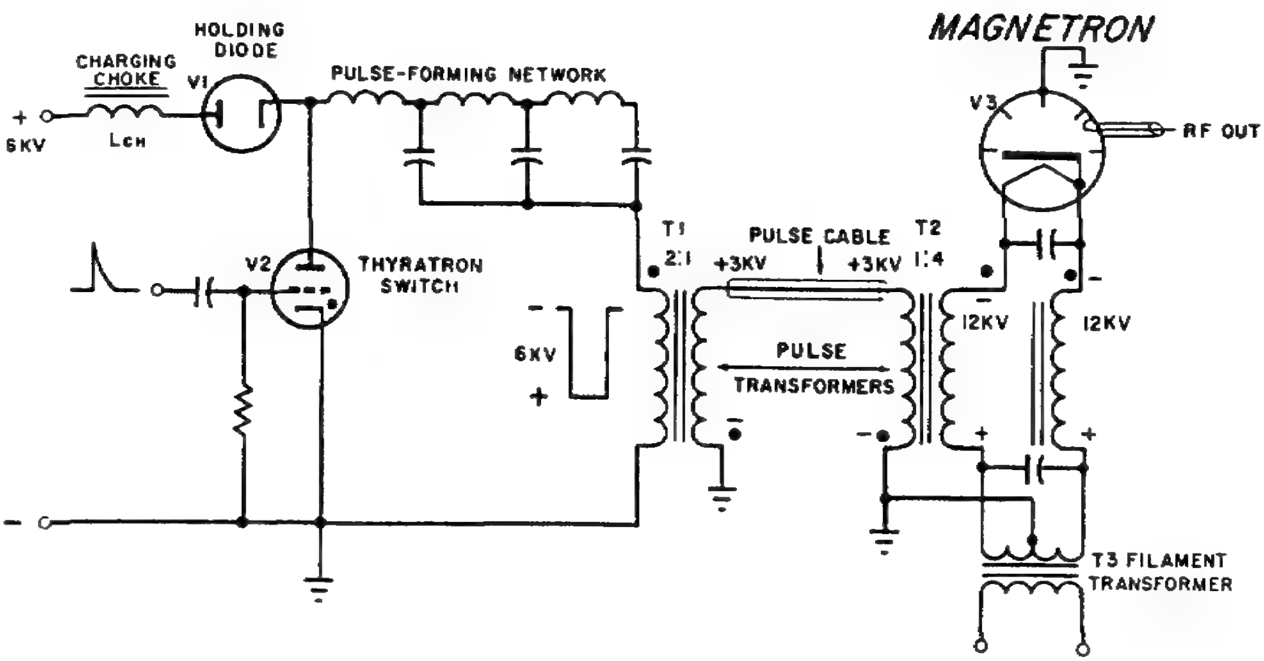
3. Impedance matching.

a. In some radar installations, the antenna is located at some distance from the transmitter. This means that a long coaxial line or waveguide must be used to connect the magnetron to the antenna. But long RF lines tend to make magnetron operation unstable. Therefore, they should not be used.

b. Figure 65 shows a solution to this problem of long lines: separation of modulator and magnetron. The magnetron is at the antenna to keep the RF transmission line as short as possible. A special coaxial pulse cable carries the

high-voltage modulator pulse to the magnetron. To prevent losses due to reflection of the pulse, the pulse cable must be terminated in its characteristic impedance. However, the impedance of the magnetron is high, approximately 1,000 ohms. So, it is not practical to build a pulse cable with a characteristic impedance of 1,000 ohms. That is why we use a pulse transformer as an impedance-matching device.

Figure 65. Pulse Transformers Used as Impedance-Matching Devices.



c. Two pulse transformers, T1 and T2, are used to match impedances in the high-level modulator in Figure 65. Pulse transformer T1 couples the pulse cable to the modulator. Not only does T1 match the impedance of the PFN and pulse cable, it also steps down the modulator pulse voltage. Lowering the pulse voltage allows the use of a smaller pulse cable with less high-voltage insulation. Pulse transformer T2 couples the low-impedance pulse cable to the high-impedance magnetron. Also, T2 steps-up the pulse voltage and thus allows the PFN to operate at a lower voltage than the magnetron.

4. Brief review.

a. The pulse transformer is a specially-designed transformer used to pass high-voltage pulses without distortion.

b. A pulse transformer has a ferro-magnetic core, is closely coupled, and has few turns in its windings.

c. It couples the high-voltage modulator pulse to the magnetron with minimum power loss by matching the low-impedance PFN to the high impedance magnetron.

d. It has bifilar secondary to isolate the magnetron filament transformer from the high-voltage pulse.

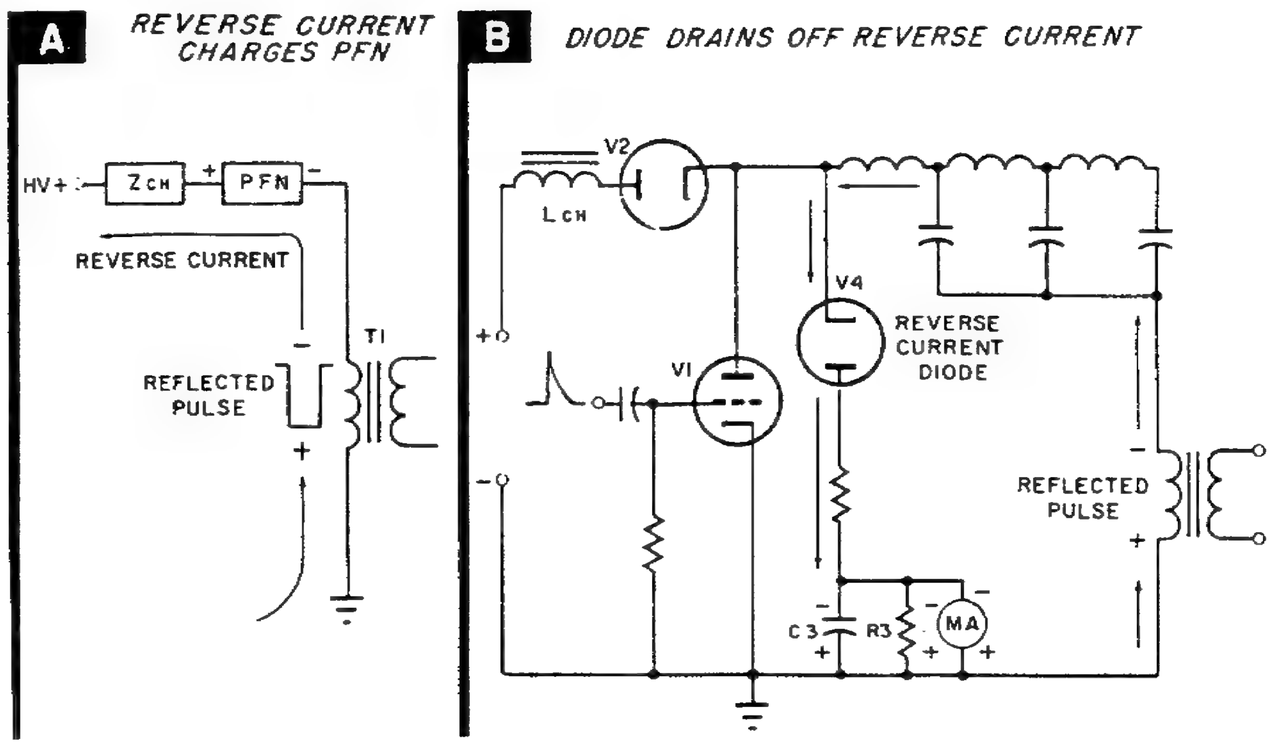
e. It steps up the pulse voltage to allow the PFN to operate at a lower voltage than the magnetron.

Learning Event 7:
MAGNETRON IMPEDANCE

1. You know that when the load (magnetron) impedance equals the pulse-forming network impedance, the voltage across the pulse transformer primary equals approximately half the voltage on the PFN at the time of the discharge. However, even though the pulse transformer does match impedance to some degree, it is impossible to keep a perfect impedance match between load and PFN at all times. The reason is that the load presented by the magnetron to the PFN varies widely from pulse to pulse. Magnetron impedance is very high until it starts to conduct. Then, impedance drops to a comparatively low value (but still higher than the impedance of the PFN).

2. If the magnetron impedance does not match the impedance of the PFN, reflections occur on the PFN. This impedance mismatch causes part of the pulse energy to be reflected back into the modulator from the magnetron. Also, each time the magnetron misfires, a large part of the pulse energy is reflected back into the modulator. When reflections occur, the voltage on the PFN does not remain constant. The reason is that the polarity of the reflected energy is the same as that of the modulator output pulse. Part A of Figure 66 shows that the pulse transformer now acts as the source instead of the load. As a result, a reverse current flows into the PFN at the end of the discharge cycle. This reverse current flows in the same direction as the charging current and thus charges the PFN. Consequently, there is already a voltage on the PFN at the start of the next charging cycle, so the PFN charges to a higher voltage than normal. Thus, with impedance mismatch, the voltage on the PFN may get so high that it breaks down the THYRATRON switch and even the PFN itself.

Figure 66. High-Level Modulator With Reverse-Current Diode.



3. So you see, when reflections occur because of impedance mismatch, the voltage on the PFN does not remain constant and the applied voltage to the pulse transformer varies. Also, if the PFN voltage is not constant from pulse to pulse, the applied voltage to the magnetron is not constant either. Likewise, magnetron power output varies, causing frequency modulation. Therefore, the PFN voltage must be held constant from pulse to pulse. This is the job of the reverse-current diode.

Learning Event 8:
REVERSE-CURRENT DIODE

1. Part B of Figure 66 shows the action of the reverse-current diode, V4. At the end of the discharge cycle, a negative pulse is reflected into the pulse transformer primary because of impedance mismatch. This negative pulse makes V4 conduct and a reverse current flows from ground, through the pulse

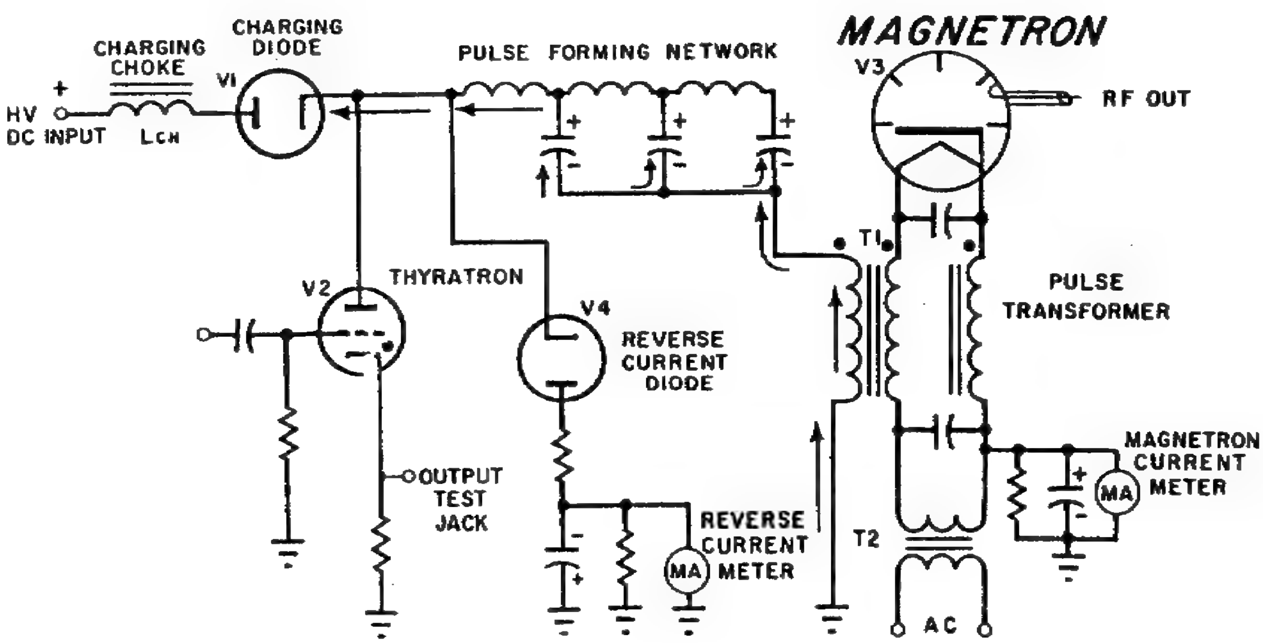
transformer primary, out of the PFN, through V4 and into the reverse-current meter circuit. Oscillations within the PFN quickly reverse the voltage on the network. This reverse voltage is drained off by V4.

2. The reverse current charges capacitor C3. When the short period of reverse-current flow is over, C3 discharges through R3. The RC time constant is long enough to maintain a stable current flow through reverse-current meter, M1.

3. Thus, the reverse-current action of V4 allows the PFN to begin charging from the same potential each time. Hence, the modulator output pulse is always kept at a constant level, thereby stabilizing magnetron operation.

4. Figure 67 shows a basic high-level modulation system with magnetron load. This circuit is not an actual high-level modulator, but it does give you some idea of how a practical high-level modulator works. Follow the step-by-step circuit action below:

Figure 67. Review of High-Level Modulation.



a. At the first instant of time, the THYRATRON switch V2 and reverse-current diode V4 do not conduct.

b. Therefore, the high-voltage power supply charges the PFN through pulse transformer primary T1, charging diode V1 and charging choke Lch.

c. Lch and PFN form a series resonant circuit. Hence, the PFN charges to nearly twice the power supply voltage.

d. When the PFN is fully charged, V1 stops conducting, thereby opening the charge circuit and preventing the PFN from discharging through the load.

Learning Event 9:
THE DISCHARGE CYCLE

1. A positive trigger (Figure 68) from the timer causes the HYDROGEN THYRATRON to conduct heavily. Now there is a discharge path for the PFN, and current flows through the pulse transformer primary and V2.

2. The PFN discharge develops a negative rectangular pulse across the pulse transformer primary. The pulse amplitude is equal to nearly half the voltage on the PFN at the time of discharge. The pulse width is equal to two TDs and depends on the PFN characteristics.

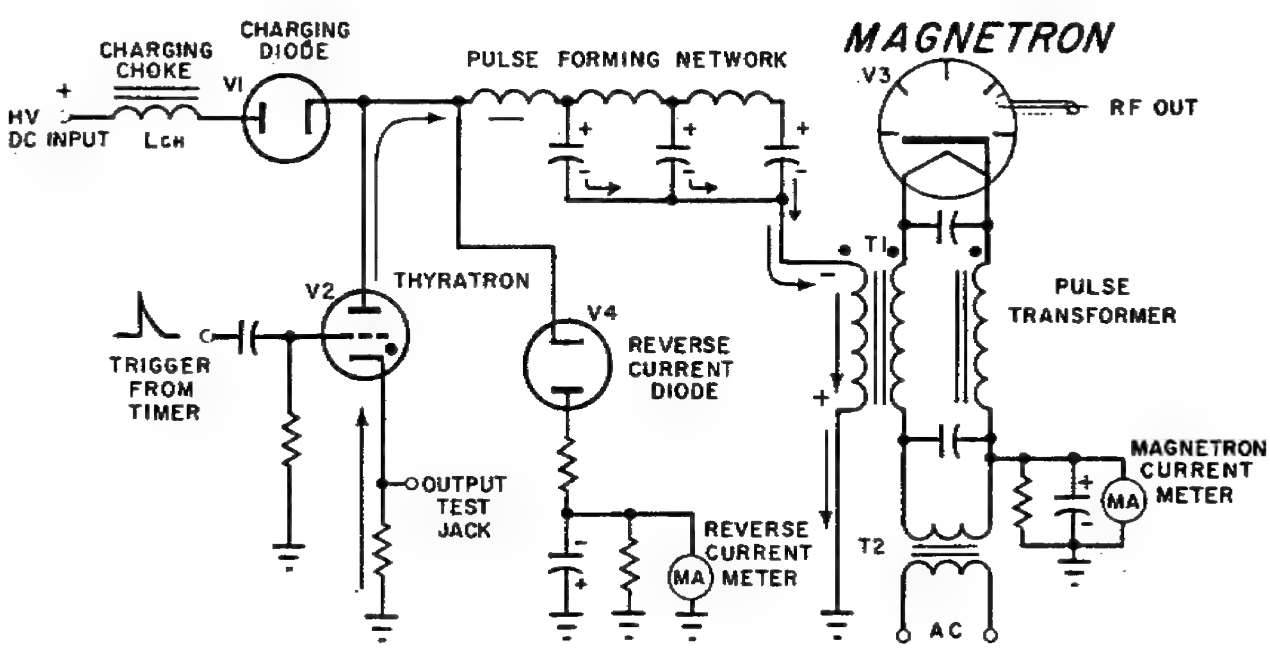
3. The pulse transformer couples this high-voltage pulse to the magnetron cathode. The magnetron oscillates for the duration of the pulse.

4. However, when the magnetron oscillates, it causes an impedance mismatch between modulator and magnetron. Hence, a negative pulse is reflected into the pulse transformer primary. A reverse current flows and charges the PFN.

5. Reverse-current diode V4 now conducts, draining the reverse charge off the PFN. This action of V4 keeps the PFN voltage constant from pulse to pulse.

6. When the PFN completely discharges, V2 deionizes and the charge cycle starts again. The HYDROGEN THYRATRON is triggered at the radar pulse-repetition frequency.

Figure 68. The Discharge Cycle.



Learning Event 10:
TROUBLESHOOTING HIGH-LEVEL MODULATORS

<u>WARNING</u>

EXTREMELY HIGH VOLTAGES, CAUSING DEATH ON CONTACT, ARE PRESENT IN THE RADAR TRANSMITTER. WHEN MAKING VISUAL CHECKS WITH POWER ON, USE JUST YOUR EYES, <u>NOT YOUR HANDS</u>. EXCEPT FOR SPECIFIC OUTPUT TESTS, <u>MAKE ALL TESTS WITH THE POWER OFF</u>. ALWAYS SHORT OUT HIGH VOLTAGE CAPACITORS BEFORE TOUCHING THEM.

1. The reason you learned how a high-level modulator works is so you can fix it when it goes bad. To do this job properly, you have to follow the standard troubleshooting procedure. Just going into the equipment haphazardly wastes a lot of time. Besides, it is extremely dangerous practice because of high voltages present in the modulator and magnetron. Actually, the modulator is just one unit within the radar system. So, before you can hope to find a bad component in the modulator, you have to determine first that the source of trouble is the modulator.

2. Trouble symptom. The first indication of trouble in a particular circuit shows up in the operation of the equipment. The trouble can be due to improper operation of the equipment, an actual malfunction within the equipment, or conditions outside the radar. Your job is to determine which of these conditions is causing the trouble. Therefore, you must know how the equipment works and what the indications are for normal operation. For example, the radar operator complains: "No signals on the indicator, but receiver grass (noise) is normal." First, check the settings of operator controls. Perhaps the radar operator is at fault. Next, check for proper meter readings, switch positions, panel lamps, and other devices built into the equipment. Knowing what each control does and what each meter or lamp indicates, helps you to troubleshoot quickly and efficiently.

a. Sectionalization. Once you have verified the symptom, the next step is to analyze and evaluate the trouble symptom to decide which section of the radar is giving trouble. Here is where your knowledge of equipment operation is important. For example, suppose during verification of the trouble symptom, you see that the magnetron-current meter reads zero. You know immediately that the trouble is in the transmitting system. You also know that the timer, receiver, and indicator systems are operating properly because there is a sweep with normal receiver grass on the indicator. There is an input to the transmitting system, but no output. Thus, you have sectionalized the trouble to the transmitting system just on the basis of your knowledge of the equipment.

b. Localization. The next step is to localize the fault to either the magnetron or modulator. Once again, check the meters and indicating lamps to decide which stage is at fault. Suppose the reverse-current meter reading is zero, but the high-voltage meter reading is higher than normal. These meter indications show that the modulator is not working. The THYRATRON is not loading the power supply and a pulse is not being developed to cause reverse current to flow. Now is the time to use a schematic and test equipment such as a synchroscope. Check for the modulator output pulse at the test jack provided for this purpose. If there is no modulator output, then you have localized the trouble to the modulator.

c. Isolation. Isolating the faulty component is the easiest step of all because there are so few components to check in the high-level modulator. Use the schematic diagram and voltage and resistance charts to isolate the faulty component quickly. But first make a visual check of the modulator. Check for lighted filaments in the THYRATRON,

charging diode, and reverse-current diode. Look for loose or broken connections, charred resistors, and loose or broken tubes. Check the tubes by substituting known good ones. Before replacing a component, make sure that the power is off.

d. Elimination of the trouble. Your job is to repair troubles. So take pride in your work by doing a neat repair job. Learn how to use your tools properly and efficiently.

e. Test circuit. After repairing the trouble, make sure the circuit works by performing an operational check.

f. So you see, the standard troubleshooting procedure is both logical and systematic. It takes you where you want to go in the shortest time. Now, let's deal just with the modulator and see what can go wrong with it.

3. Trouble symptom. No modulator output pulse.

Assume you've localized the trouble to the modulator. The first step in troubleshooting the modulator is to check the output pulse. You can do this easily by connecting a synchroscope to the test jack provided for this purpose. If there is no modulator output pulse, isolate the trouble by making the following checks:

(1) Check the input trigger pulse to the THYRATRON. If the trigger is not present, the THYRATRON won't fire. Then, you will have to check the timer unit. If the trigger is present, measure its amplitude. If the amplitude is too low, the trigger will not fire the THYRATRON.

(2) Check the modulator plate voltage. Usually, there is a meter on the modulator panel for this purpose. If the meter indicates no modulator plate voltage, then check the output of the high-voltage power supply.

(3) Look for lighted filaments in the THYRATRON and charging diode. Replace the tubes with known good ones.

(4) Check each of the components in the modulator. An open charging choke, PFN, or pulse transformer primary will cause loss of modulator output.

4. Trouble symptom. Modulator pulse present but distorted.

If the modulator output pulse is present, check for proper waveshape on the synchroscope. Examine it carefully for negative polarity, sharp leading and trailing edges, correct amplitude, and proper pulse width. If the modulator output pulse is distorted, isolate the trouble by making the following checks:

(1) Measure the pulse amplitude. If it is too low, check the components in the charge circuit. Check the high-voltage power supply, the charging choke, PFN, and pulse transformer. Also check the THYRATRON; its conducting resistance may have increased.

(2) Measure the pulse width. If the pulse width or shape is not correct, check the PFN.

(3) Check the trailing edge of the pulse. If there are too many oscillations following the pulse, check the reverse-current diode circuit. Replace the diode with a known good one.

5. Final Summary.

a. A radar transmitter consists of two major units: modulator and magnetron. The modulator develops rectangular high-voltage DC pulses which cause the magnetron to generate bursts of RF energy. The modulating pulse may be formed either by low-level modulation or high-level modulation. This lesson describes the operation of a high-level modulation system in which the pulse is formed at a high power level.

b. A basic high-level modulator consists of a high-voltage DC power supply, a charging impedance, a pulse forming network, and a switch. At the first instant, the high-voltage power supply charges the PFN to several thousand volts through the charging impedance. After the PFN is fully charged, the switch closes, discharging the PFN through the load (magnetron and its pulse transformer).

c. Practical high-level modulators use DC resonant charging to increase the pulse amplitude and efficiency of the system. In DC resonant charging, the PFN is charged through a charging choke and charging diode. The charging choke allows the PFN to charge to a voltage nearly twice the power supply voltage. The charging diode in series with the

charging choke prevents discharge of the PFN until the switch closes. The switch is a HYDROGEN THYRATRON, which is triggered at the PRF of the radar. When the THYRATRON fires, the PFN discharges through the pulse transformer primary, developing a negative DC pulse with an amplitude equal to half the voltage on the PFN. The pulse width is equal to two TDs and depends on the PFN characteristics.

PRACTICE EXERCISE
(Performance-Oriented)

In each of the following exercises, select the ONE answer that BEST completes the statement or answers the question. Indicate your solution by circling the letter opposite the correct answer in the subcourse booklet.

1. The Guillemin line, shown in Figure 69, is a specially designed pulse-forming network that employs inductive coupling between the loops of wire. The reason for using inductive coupling is to

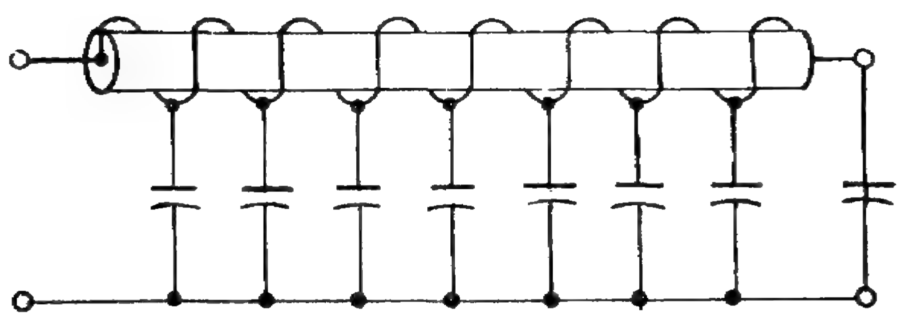
   a. increase the charge on the PFN.

   b. reduce the effects of reverse current.

   c. remove undesired oscillations from the PFN.

   d. decrease the time required to charge the PFN.

Figure 69. Guillemin Pulse-Forming Line.



2. The operation of a HYDROGEN THYRATRON differs from the operation of conventional thyratrons in that the HYDROGEN THYRATRON

   a. has a long ionization time.

   b. conducts only when the grid voltage is zero.

   c. conducts only when the grid is positive in respect to the cathode.

   d. can be cut off by applying a negative voltage to the control grid or a positive voltage to the plate.

3. The HYDROGEN THYRATRON'S positive control grid characteristic is made possible by

   a. using hydrogen gas.

   b. shielding the cathode from the plate.

   c. enclosing the plate wire in a glass sleeve.

   d. preventing interaction between the plate-lead wire and the outside of the grid structure.

4. If a DC resonant charging choke is used as the charging impedance in a high-level modulator, the choke is used to form a

   a. series-resonant circuit with the capacitance of the PFN.

   b. parallel-resonant circuit with the capacitance of the PFN.

   c. series-resonant circuit with the capacitance of the THYRATRON.

   d. parallel-resonant circuit with the capacitance of the pulse transformer windings.

5. The necessity of timing a THYRATRON to conduct at the instant when the pulse-forming line is charged at its greatest potential is eliminated by

   a. charging the pulse-forming line through a diode.

   b. DC resonance charging of the pulse-forming line.

   c. connecting a charging inductor across the circuit.

   d. using a HYDROGEN THYRATRON in conjunction with a Guillemin line.

6. The transmitter shown in Figure 65 uses two pulse transformers to transfer the modulator pulse to the magnetron. The reason for using a bifilar secondary winding on T2 is to

   a. permit a 4:1 step-up of voltage.

   b. allow the use of a conventional filament transformer.

   c. reduce the effects of the changing magnetron impedance.

   d. permit the use of a smaller pulse cable with less high-voltage insulation.

7. The performance of a high-level modulator can be improved by coupling the pulse from the modulator to the magnetron through a pulse transformer. In addition, the use of a pulse transformer has the advantage of

   a. eliminating the magnetron filament transformer.

   b. permitting higher voltages in the pulse-forming network.

   c. reducing the potential between cathode and ground of the magnetron.

   d. eliminating the need for long transmission lines between the transmitter and the antenna.

8. If the characteristic resistance of the PFN shown in Figure 65 is not equal to the magnetron's impedance, the pulse applied to the magnetron will be distorted. This impedance mismatch will also cause the PFN to

   a. charge to a lower voltage on each succeeding charge cycle.

   b. charge to a higher voltage on each succeeding charge cycle.

   c. produce a pulse that has a duration time of less than two TDs.

   d. produce a voltage that will cause the thyratron to conduct prematurely.

SITUATION

Assume that the circuit shown in Figure 70 represents the schematic diagram of the transmitter in an air surveillance radar set. The high-level modulator uses an artificial transmission line that has a characteristic resistance of 1,000 ohms and time delay of 0.75 microseconds.

Exercises 9 through 14 are based on the above situation.

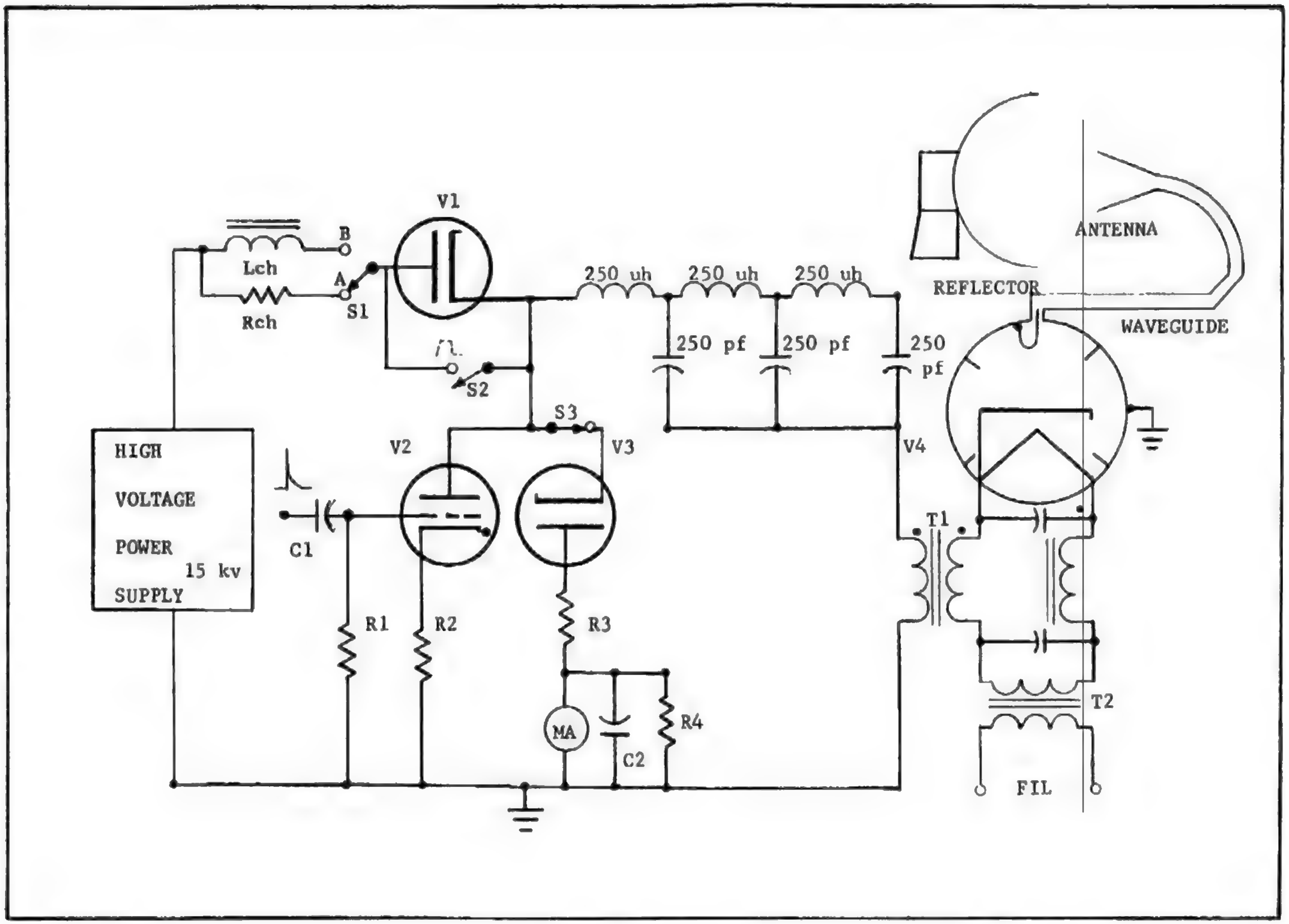


Figure 70. Radar Transmitter Schematic.

9. Assume that the load resistance of the high-level modulator shown in Figure 70 is equal to 1,000 ohms and that a positive trigger voltage causes tube V2 to conduct. The PFN will discharge and the amplitude of the pulse developed across the primary of transformer T1 will be a negative

   a. 15 KV with a duration time of 1.5 microseconds.

   b. 15 KV with a duration time of 0.75 microseconds.

   c. 7.5 KV with a duration time of 1.5 microseconds.

   d. 7.5 KV with a duration time of 0.75 microseconds.

10. The charging resistance Rch is used to control the charge time of the pulse-forming network and to

    a. prevent the PFN from discharging before V2 conducts.

    b. control the duration of the voltage developed across T1.

    c. allow the PFN to charge to a voltage that is approximately twice the power supply voltage.

    d. prevent tube V2 from short-circuiting the high-voltage power supply during the discharge of the PFN.

11. The current flow through the switching tube V2 will cease when

    a. switch S3 is opened.

    b. a negative trigger is applied to the grid of V2.

    c. the voltage across the pulse-forming network is zero.

    d. the pulse-forming network is completely charged to 15 KV.

12. If the milliammeter shown in the cathode circuit of V3 (Figure 70) indicates an abnormally high current reading, the probable cause of this reading is

   a. a change in the magnetron's impedance.

   b. a change in the value of Rch.

   c. an open charging resistance.

   d. a decrease in the pulse repetition frequency (PRF).

13. The network composed of C2 and R4 is used to filter the pulsating current through V3 and to produce an average current reading on the milliammeter. Electron tube V3 will conduct when

   a. V1 stops conducting.

   b. the PFN becomes fully charged.

   c. V2 is triggered by the positive timing pulse.

   d. the magnetron causes a negative pulse to be reflected back into the primary of T1.

14. When tube V2 conducts in the modulator circuit shown in Figure 70, then pulse-forming network will discharge through

   a. the primary of T1, R2, and V2.

   b. the primary of T1, R4, R3, and V3.

   c. the primary of T1, high-voltage power supply, Rch, and V1.

   d. V1, Lch, high-voltage power supply, R4, C2, milliammeter, R3, and V3.

SITUATION

Assume that switch S1 is moved to position B in the circuit shown in Figure 70, and that the pulse repetition frequency of the radar set is 400 pulses per second.

Exercises 15 through 20 are based on the above situation.

15. Assume that switch S2 is closed in the circuit shown in Figure 70. To produce the maximum output from the pulse-forming network, the resonant frequency of the pulse-forming network capacitance and Lch should be approximately

a. 100 Hz.

b. 200 Hz.

c. 400 Hz.

d. 800 Hz.

16. If the pulse-forming network is allowed to charge through the DC resonant charging choke, the network will charge to approximately

a. 15 KV and will produce an output pulse of approximately 7.5 KV.

b. 15 KV and will produce an output pulse of approximately 15 KV.

c. 30 KV and will produce an output pulse of approximately 15 KV.

d. 30 KV and will produce an output pulse of approximately 30 KV.

17. The charging diode is used in conjunction with the DC resonant charging choke to

a. permit the use of more than one PRF.

b. maintain a constant charge across the PFN from pulse to pulse.

c. prevent the high-voltage power supply from being short circuited when V3 conducts.

d. allow the PFN to charge to a voltage that is approximately twice the power supply voltage.

18. The pulse transformer used to couple the modulator's output pulse to the magnetron is different from a conventional transformer in that its windings are designed to have

    a. loose coupling and few turns.

    b. close coupling and few turns.

    c. loose coupling and many turns.

    d. close coupling and many turns.

19. The frequency at which the antenna shown in Figure 70 sends the RF pulses into space is determined by the

    a. TD of the PFN.

    b. number of sections used in the PFN.

    c. resonant frequency of the magnetron.

    d. frequency of the positive triggers applied to V2.

20. If the antenna shown in Figure 70 is to be used for both transmitting and receiving, an additional section of waveguide will be connected to the existing waveguide. At the junction of the two waveguides, a component is placed which will allow one antenna to be used for both transmitting and receiving. This component is called

    a. a relay.

    b. a duplexer.

    c. a thyratron.

    d. an interlock.

Check your answers with lesson 2 solution sheet.

LESSON THREE

RESONANT CAVITIES AND MAGNETRONS

TASK

Describe resonant cavities and magnetron operations, recognize coupling and tuning techniques employed with resonant cavities and magnetrons, identify different types of magnetrons and describe their modes of operation.

CONDITION

Given this lesson, pencil, and paper.

STANDARD

Demonstrate competency of task skills and knowledge by correctly responding to 75 percent of the multiple-choice test covering radar transmitters.

REFERENCE

TC 11-67

Learning Event 1: RESONANT CAVITIES

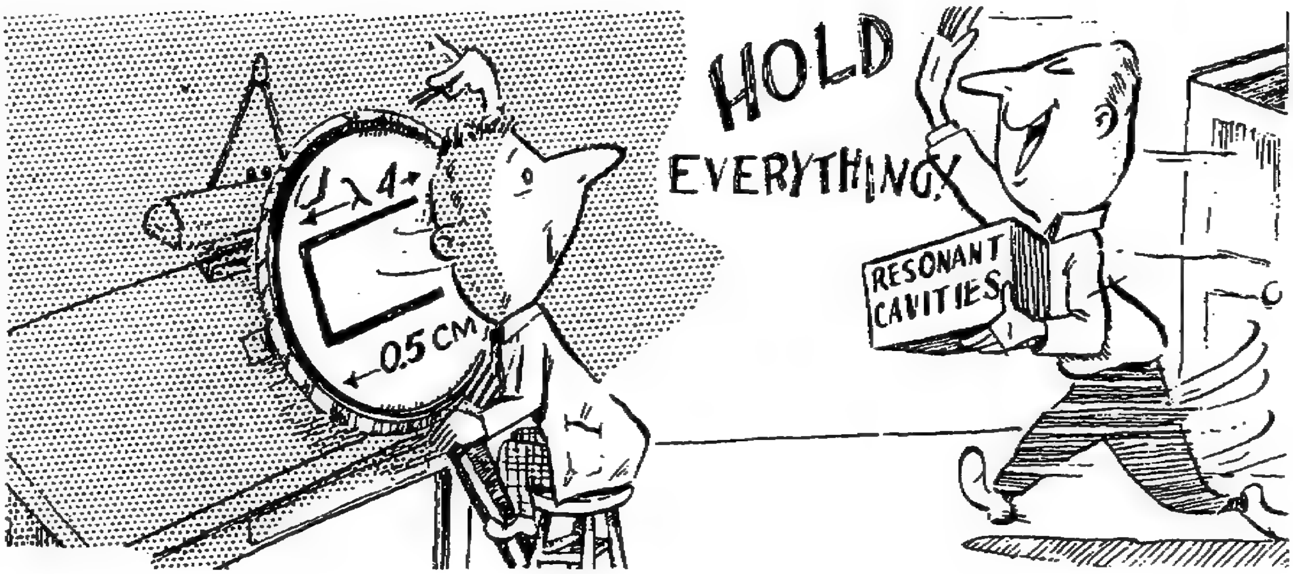
1. General.

a. A coil and capacitor form a resonant circuit when connected together either in a series or parallel arrangement. The higher the resonant frequency you want, the smaller are the capacitor and coil that you need. Resonant circuits operating at ultra-high frequencies (UHF) have extremely small values of inductance and capacitance. The values are so small in fact, that at about 500 megahertz, the use of coils and capacitors becomes impractical. So, instead of using a coil and capacitor at these UHF frequencies, we can use a section of transmission line as a resonant circuit.

b. You learned in a previous lesson how a transmission line section serves as a resonant circuit. Transmission lines are similar to resonant circuits, except that the inductance and capacitance are distributed instead of being lumped values. Just like ordinary resonant circuit components,

transmission lines must be made smaller when you want to increase their resonant frequency. When the resonant frequency required is so high that it is impractical to use a transmission line section, we use a component called a resonant cavity (Figure 71).

Figure 71. Resonant Cavities are Used at Microwave Frequencies.



2. A resonant cavity is a type of resonant circuit.

A resonant cavity is a type of resonant circuit used at microwave frequencies. You will learn in this lesson why resonant cavities are necessary in microwave radio and radar equipment. You will also see how resonant cavities are constructed and how they operate. Next, you will learn how to tune resonant cavities, and how to couple energy into them and out of them. Finally, you will see several practical applications of resonant cavities as they are used in microwave oscillators and test equipment.

3. Before we talk about resonant cavities, let's review tuned circuits.

a. You know that a combination of inductance and capacitance is a tuned or resonant circuit. To increase the resonant frequency of a tuned circuit, you must use a lower value of inductance and capacitance. Resonant circuits operating at very high frequencies (VHF) consist of only a few loops of wire for the inductance and very small capacitor.

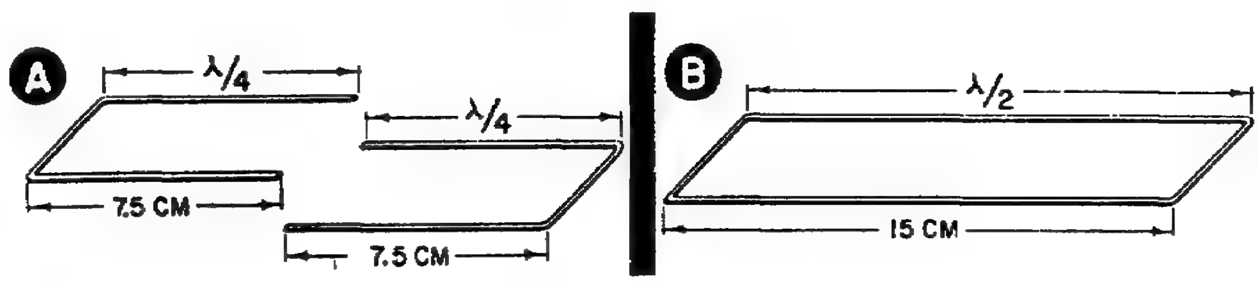
b. The sizes of the coil and capacitor that resonate at about 500 megahertz are still smaller. For example, the tuned-circuit coil in a typical UHF communications receiver operating at 400 megahertz consists of only one turn of wire. Its capacitor has only two plates. To raise the resonant frequency of this tuned circuit, all you need is a half turn of wire with its distributed capacity. This half turn of wire is in effect a section of closed-end, two-wire transmission line.

4. Transmission line sections are used as resonant circuits.

a. You know from a previous lesson that sections of transmission line are used as resonant circuits. We use resonant sections of transmission line at UHF frequencies where coils and capacitors are not practical.

b. Transmission lines are similar to coils and capacitors in that they too must be made smaller to increase their resonant frequency. A transmission line cut to resonate at 1000 megahertz is only a few centimeters long and if you cut it shorter to increase its resonant frequency, its use is awkward. However, if you take two sections, each cut for 1000 megahertz as in Part A of Figure 72, and connect them in parallel as in Part B of Figure 72, the length of the line is doubled. But, the resonant frequency of the combined sections remains the same, at 1000 megahertz.

Figure 72. Two Quarter-Wave Sections of Transmission Line Connected in Parallel.



5. What happens if we connect more sections of transmission line in parallel?

a. Before answering this question, review the following important points:

(1) You will recall that if you connect two coils of equal value in parallel, the total inductance is equal to one-half the inductance of either coil.

(2) Connecting two capacitors of equal value in parallel gives the opposite result, the total capacitance is equal to twice the value of either capacitor.

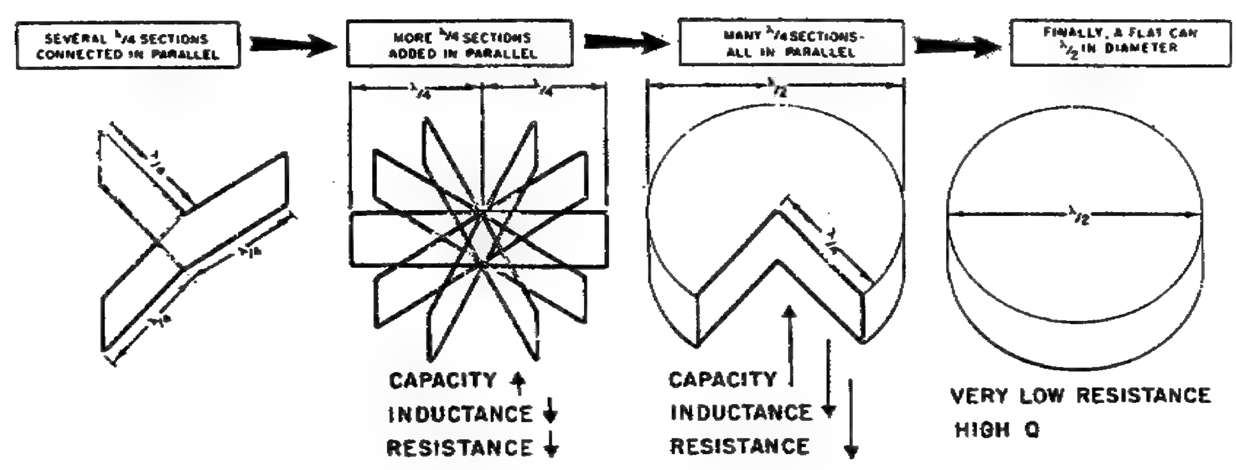
(3) Resistors are similar to coils. If you connect two resistors of equal value in parallel, the total resistance is only one-half of either resistor.

(4) Each quarter-wave section of the same type of transmission line has the same amount of distributed inductance, capacitance, and resistance. If we connect identical sections in parallel, we connect the individual resistance, inductance, and capacitance in parallel.

b. You see then, that as we parallel identical transmission line sections, the total inductance decreases in the same proportion that the total capacitance increases. The resonant frequency of the combined lines, therefore, is the same as each individual line. We can add as many lines in parallel as we want and the resonant frequency does not change.

c. The total resistance changes though and this fact is very important. The total resistance keeps getting smaller as we add more sections of line. As the resistance decreases, the Q, or figure of merit rises. This means the selectivity and efficiency of the circuit go up. If we continue to add more sections in parallel, as shown in Figure 73, we finally get a very high Q, flat, metal box or can, which is resonant only for an extremely narrow frequency range. We call this metal can a resonant cavity.

Figure 73. Development of Resonant Cavity.



6. Some characteristics of resonant cavities.

a. You have seen that a resonant cavity is a space bounded by walls. When you excite the cavity by applying electrical energy to it, all the energy is contained inside the walls.

b. When we apply energy to ordinary tuned circuits and transmission-line tuned circuits, we usually speak in terms of voltage and current. But when we excite a resonant cavity, we cannot speak only in terms of voltage and current because most of the energy inside the walls is contained in the electric and magnetic fields. There is some electron flow, however, but it is limited to a thin layer of metal on the inside surface of the walls. Sometimes, the inside surfaces of the walls are silver-plated or gold-plated to reduce heat losses due to resistance. Plating the walls makes the Q of the cavity even higher, and cavities with a Q of 30,000 are not uncommon. There is no current flow on the outside of the cavity, so there is no radiation loss. Since current flows only on the inside walls, some cavities are made from nonconducting materials. The inside walls are then sprayed with a thin layer of metal, or covered with metal foil.

7. Comparing resonant cavities with transmission lines.

a. Resonant cavities are similar to transmission lines in two ways:

(1) The fundamental resonant frequency of transmission lines and resonant cavities is determined by their size.

(2) Transmission lines and resonant cavities can have different forms or shapes.

b. Let's examine both of these similarities.

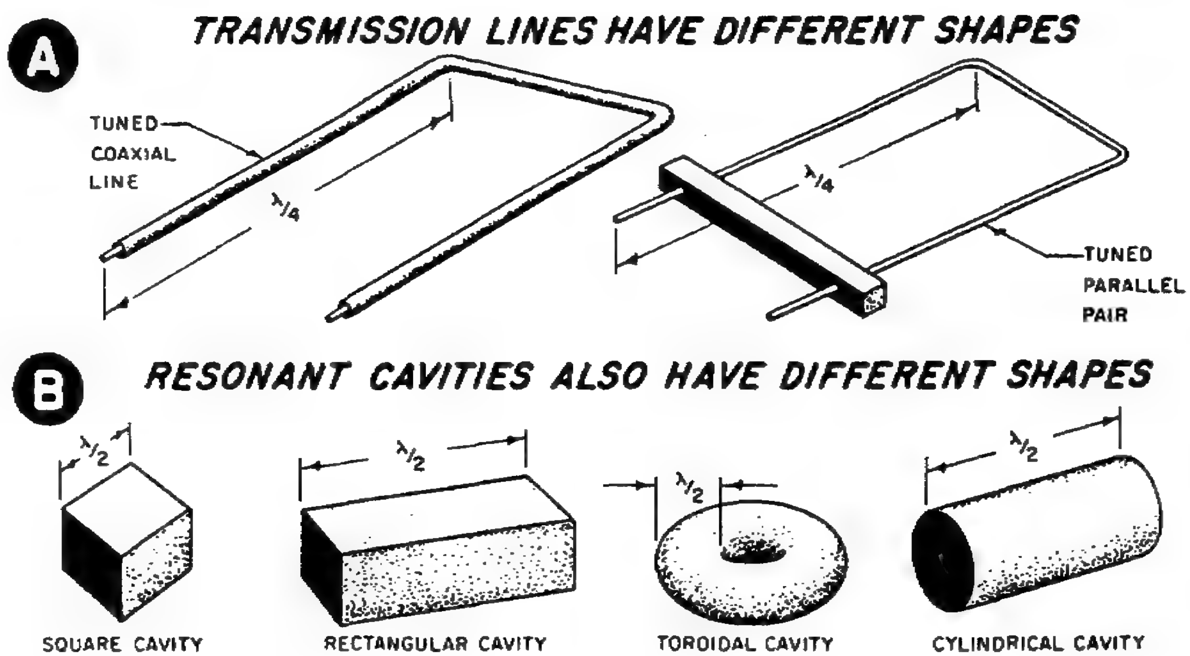
8. First, size determines resonant frequency.

You know that the size of a transmission line determines its resonant frequency. For example, a one-quarter wavelength section of transmission line acts as a parallel resonant circuit, and it is the shortest length that oscillates. Similarly, the area within the walls of a resonant cavity determine the resonant frequency. A resonant cavity must be at least one-half wavelength in dimension to oscillate.

9. Different forms can be used.

The two transmission line sections in Part A of Figure 74 are both closed-end, one-quarter wavelength sections. One section is a coaxial line, and the other section is a parallel pair. Although the lines differ physically they are both resonant circuits. They might even be tuned to the same frequency. Just as transmission lines can have different shapes, so can resonant cavities. You have already seen a resonant cavity in the shape of a flat can. Other cavity shapes (Part B of Figure 74) are square, rectangular, toroidal (doughnut shaped), and cylindrical.

Figure 74. Types of Transmission Line and Resonant Cavity Tuned Circuits.



10. A brief review.

a. Combinations of coils and capacitors are impractical as resonant circuits above 500 megahertz.

b. Transmission lines are impractical as resonant circuits above 1000 megahertz.

c. Therefore, at microwave frequencies, a resonant cavity is used as a tuned circuit instead of LC circuits or transmission lines.

d. A resonant cavity is a hollow chamber with conducting walls.

e. All energy generated in a resonant cavity is contained within its walls.

f. Resonant cavities have very little resistance and a very high Q.

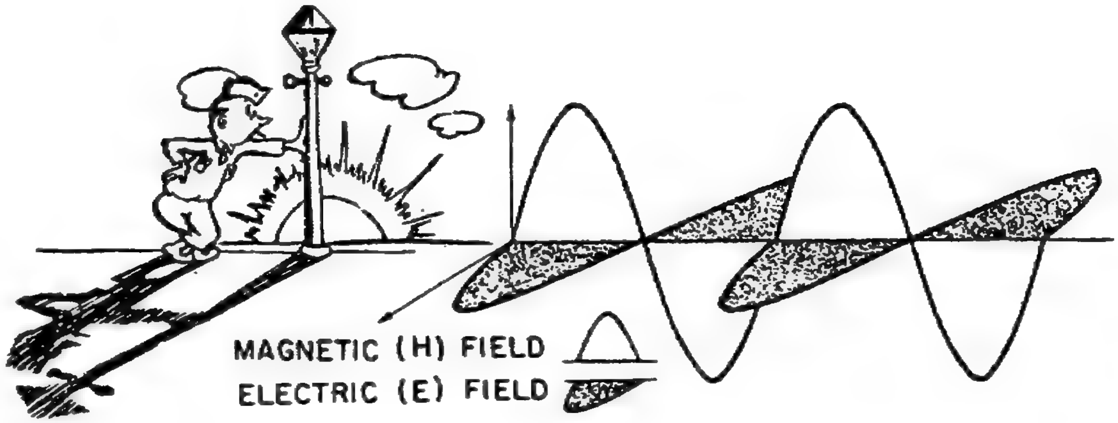
g. Now that you know the characteristics of a resonant cavity, let's see how they work.

11. We can best describe the operation of a resonant cavity in terms of fields.

a. Since resonant cavity electron flow is limited to the inside walls, we will explain the operation of a cavity in terms of fields. We will also use the voltage and current curves associated with transmission lines to represent the field intensities.

b. Current flow in an antenna creates a magnetic field, called the H field, that encircles the antenna. The magnetic field produces an electric field, called the E field, at right angles to itself. This combination of H and E fields, shown in Figure 75, is called the electromagnetic field.

Figure 75. The Electromagnetic Field.



c. The electromagnetic field in a resonant cavity may be in different positions depending upon the size of the cavity, the method of coupling, and the frequency of the signal fed into the cavity. The different positions, or patterns of the fields are called modes.

12. What are modes?

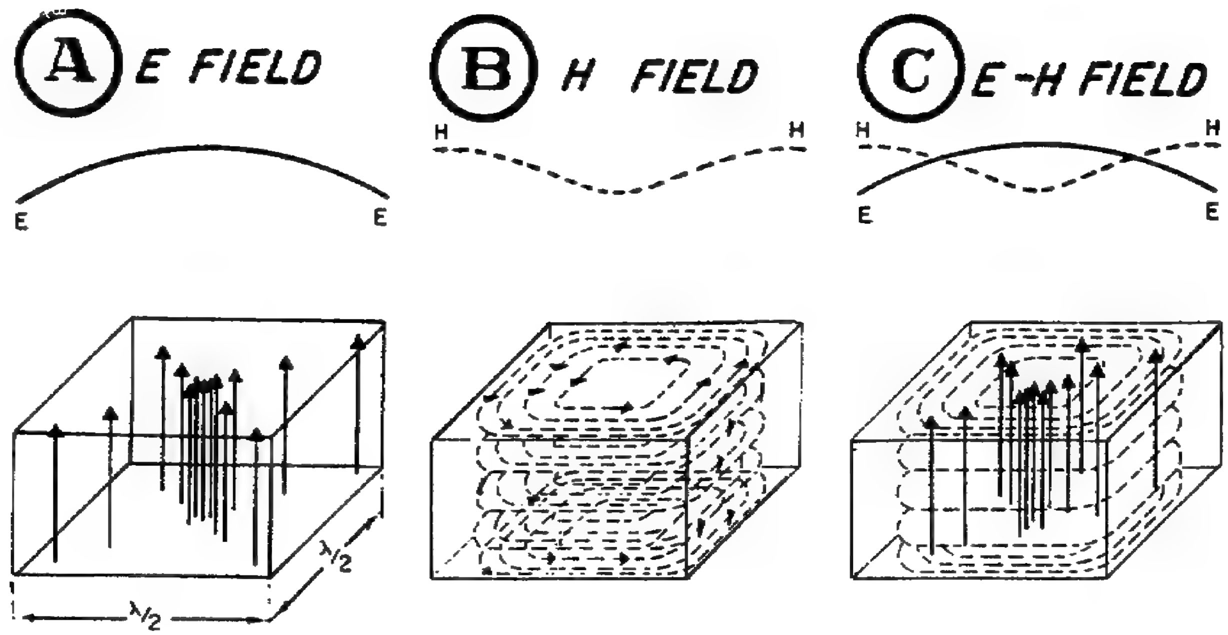
a. So far, you know that a resonant cavity can be one of several different shapes and, when excited, the cavity contains an electromagnetic field. The electric field is always perpendicular to the magnetic field, but the pattern (mode) of the combined fields inside the cavity may vary.

b. For example, the electric field may be parallel to the width, height, or length of the cavity. These patterns or forms of operation are only three among many possibilities that we term "modes of operation." As a repairman, it is not necessary for you to be skilled in mode operation. But, it will help in your work to know there are different ways (or modes) to excite a cavity. Therefore, an explanation of the PRIMARY mode of operation follows.

13. The PRIMARY mode of operation.

a. The PRIMARY mode of exciting a resonant cavity is shown in Figure 76. The arrows in Part A of Figure 76 represent the electric (E) field and indicate the field direction and intensity. Consider the electric field as voltage, and the areas of maximum voltage are where the lines are the densest. You can see that there is one complete electric field pattern along the length and another across the width of the cavity. These dimensions are one-half wavelength.

Figure 76. PRIMARY Mode of Oscillation During First Half Cycle.

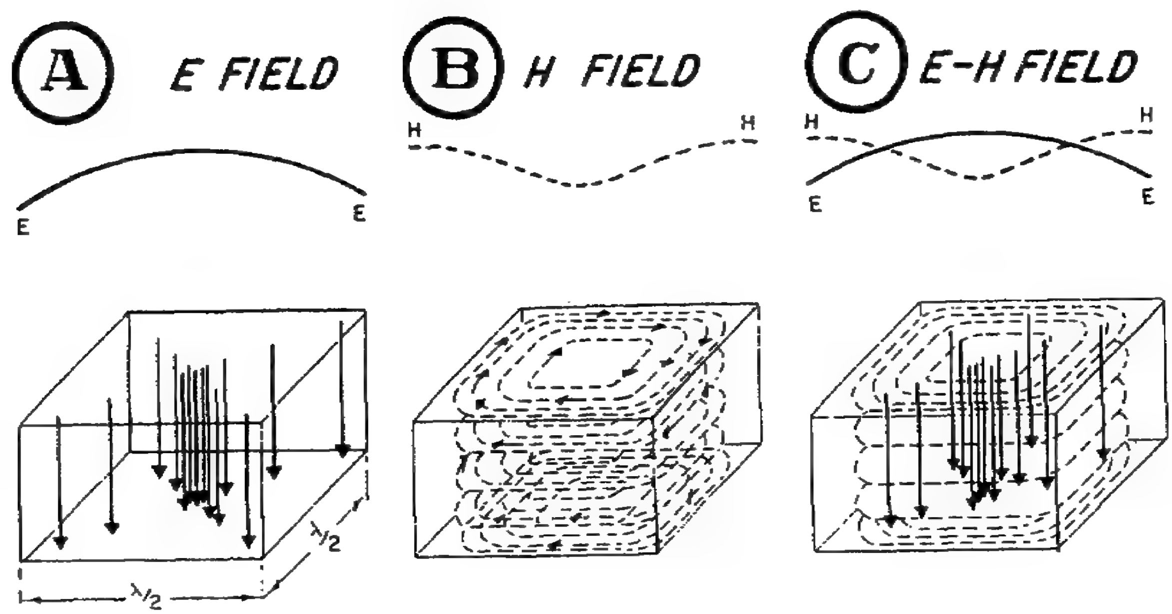


b. Now look at Part B of Figure 76. The dotted lines represent the magnetic (H) field perpendicular to the electric field. Consider the magnetic field as current, although the only current flow is on the inside surface of the walls.

c. Part C of Figure 76 shows the combination of electric and magnetic fields of the cavity represented with the voltage and current curves associated with transmission lines. This illustration shows the fields stationary. Actually, the fields are oscillating.

d. Figure 76 shows the fields during one alternation, or one-half cycle. During the next half cycle, the direction of the fields reverses. This is shown in Figure 77.

Figure 77. PRIMARY Mode of Oscillation During Second Half Cycle.



14. The main points to remember about the fields of a resonant cavity.

a. The energy in a resonant cavity is contained in its electric (E) and magnetic (H) fields.

b. The E and H fields are always perpendicular to each other.

c. The way in which the fields are positioned within the cavity is called the mode of operation.

d. For the PRIMARY mode of operation, the length and width of a resonant cavity is one-half wavelength and the height is less than one-half wavelength.

e. We have discussed how the size of a cavity determines its resonant frequency. Now, let's see how size applies to tuning.

15. Methods of tuning a resonant cavity.

a. There are four principal methods of tuning a resonant cavity using the following:

(1) A movable plunger.

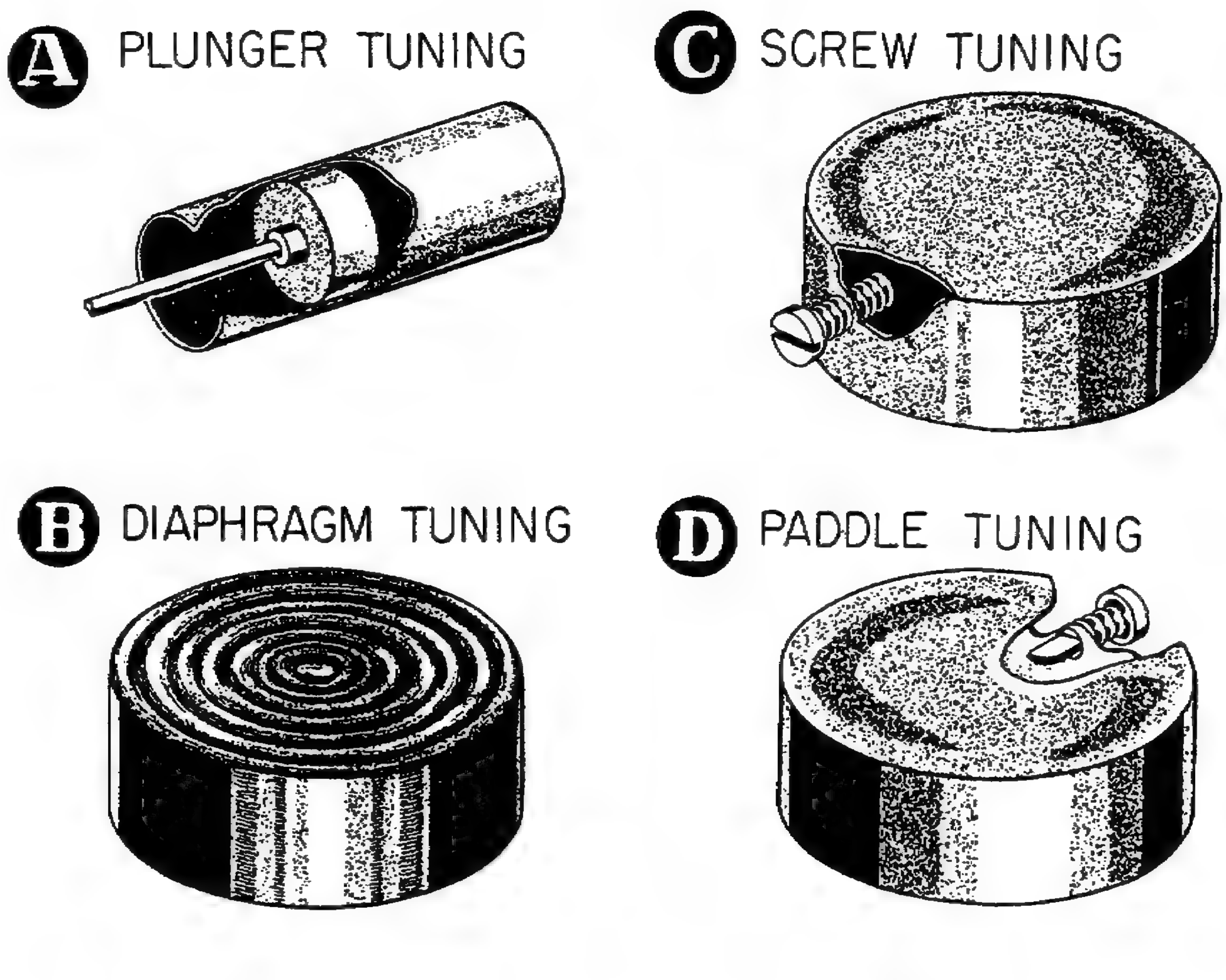
(2) An expanding diaphragm.

(3) An adjustable screw.

(4) A rotating paddle.

b. These methods are used for all cavities, regardless of the manner in which the cavities are excited. Let's look at each one of these methods of tuning and see how they work. They are all shown in Figure 78.

Figure 78. Tuning Methods.



16. First, plunger tuning.

You see in Part A of Figure 78 that one wall of the cavity is a movable plunger, resembling a piston in a cylinder. You adjust the plunger to change the size of the cavity. The effect is similar to what happens when you change the length of a coil. Inserting the plunger deeper reduces the cavity and inductance, causing the frequency to go up. If you withdraw the plunger, the inductance goes up and frequency goes down.

17. Next, diaphragm tuning.

An example of diaphragm tuning is shown in Part B of Figure 78. You see that one wall of the cavity is pleated. You adjust this wall, called a diaphragm, to reduce or increase the size of the cavity. The effect is similar to what happens when you change the distance between the plates of a capacitor. If you make the distance between the diaphragm and the bottom of the cavity smaller, capacitance increases, causing the frequency to go down. If you make the distance larger, the capacitance goes down and frequency goes up.

18. Now, screw tuning.

An example of screw tuning, sometimes called slug tuning, is shown in Part C of Figure 78. An adjustable screw is inserted through one wall of the cavity. Turning the screw changes the inductance of the cavity. As you turn the screw so that it penetrates further into the cavity, you confine the magnetic field to a smaller space, and reduce the inductance. This increases the resonant frequency. As you turn the screw in the opposite direction, you shorten its extent into the cavity. This increases its inductance and the resonant frequency goes down.

19. Paddle tuning.

Another method similar to screw tuning is paddle tuning. Part D of Figure 78 shows that one wall of the cavity has a paddle that you rotate. Turning the paddle to a position more nearly perpendicular to the magnetic field lowers the cavity inductance and raises the cavity resonant frequency. Turning the paddle to a position more nearly parallel to the magnetic field raises the cavity inductance, and lowers the cavity resonant frequency. Both the screw and paddle methods of tuning compare to inserting a brass slug into an IF coil to adjust the inductance.

20. Summary of tuning methods.

a. There are four principal methods of tuning a cavity: using a plunger, a diaphragm, a screw, or a paddle.

b. The plunger and diaphragm methods of tuning vary the size of the cavity to change its resonant frequency.

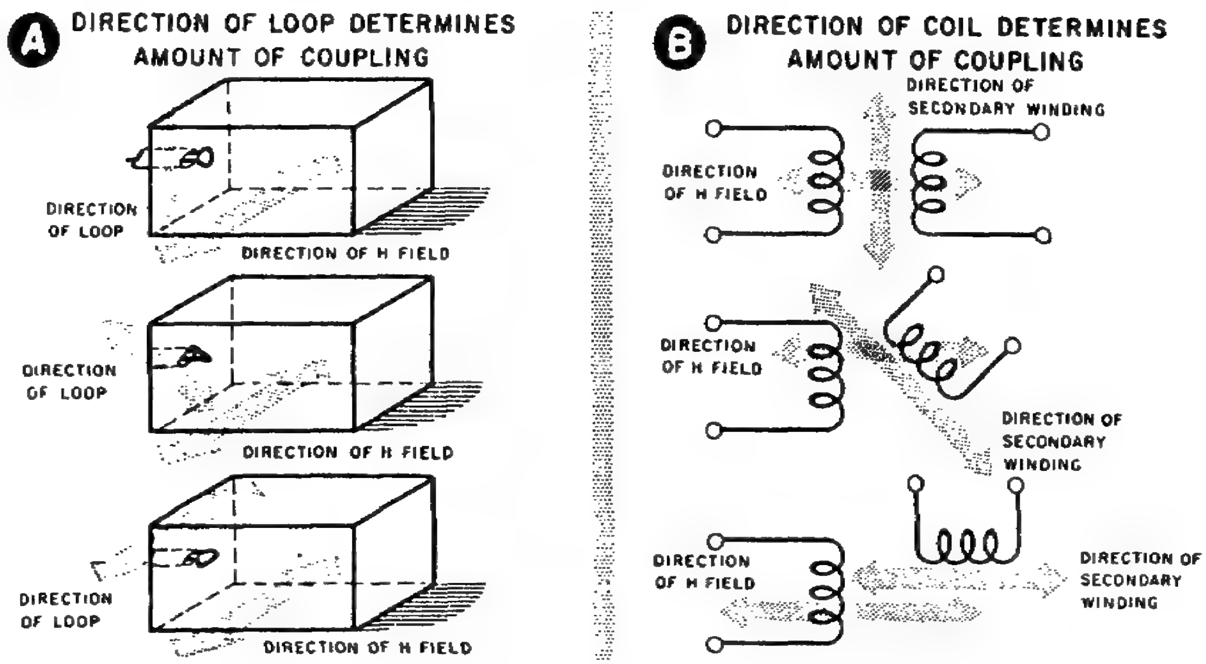
c. The screw and paddle methods of tuning change the resonant frequency of the cavity without varying the size.

d. Now that you know the various methods used to tune resonant cavities, let's get back to the main purpose of resonant cavities, that is, to generate frequencies higher than 1000 megahertz. First of all, you know that a resonant cavity must be excited to make it oscillate, that is, energy must be fed to it from an external source. Once the cavity is oscillating, we must couple the energy out of the cavity. There are three principle ways that energy is put into or removed from a cavity. You use the same methods for either operation. These three methods are described in the paragraphs that follow.

21. Loop coupling.

a. A conductor in the shape of a loop is inserted into the area of maximum magnetic lines of force as shown in Part A of Figure 79. In effect, this method of coupling is comparable to coupling between the primary and secondary of a transformer as shown in Part B of Figure 79. When the loop is perpendicular to the lines of force, maximum energy is transferred. This fact is also true of a transformer. The coils of the transformer are parallel to each other, and the magnetic lines of force are perpendicular to the coils.

Figure 79. Loop Coupling Compared to Transformer Coupling.



b. If you rotate the secondary winding of the transformer in Part B of Figure 79, the primary magnetic field cuts the secondary at an angle less than ninety degrees, and less energy is transferred to the secondary. The loop in Part A of Figure 79 acts the same way. If you turn the loop at an angle away from the perpendicular, less energy is transferred. With a rotating loop, you can vary the amount of coupling. Remember, you get maximum coupling when the loop is perpendicular to, and in the area of, maximum magnetic lines of force.

c. Maximum magnetic lines of force means that there is maximum current in this area of the cavity. You already know an area of maximum current has minimum impedance and minimum voltage. We say then, that loop coupling is characterized by the following:

(1) High current.

(2) Low voltage.

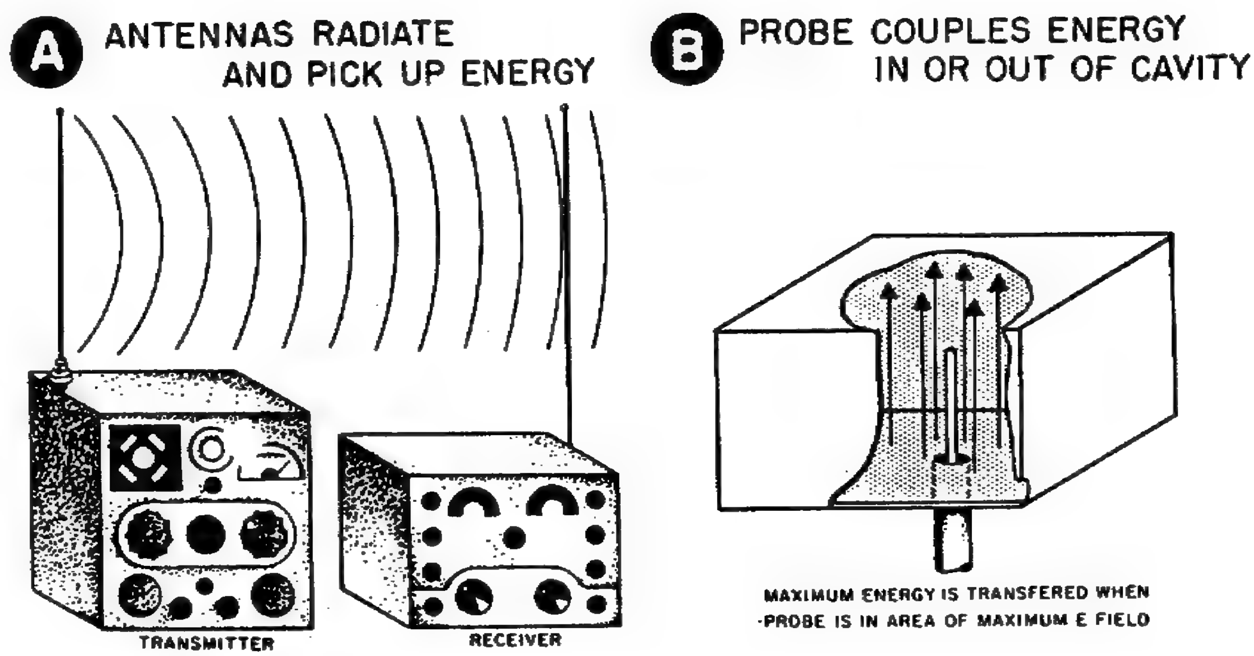
(3) Low impedance.

d. A second method of coupling energy to or from a cavity is with a probe.

22. Probe coupling.

a. Probe coupling operates, in effect, like a transmitting or receiving antenna. When you use a probe to excite a cavity, it acts as a transmitting antenna. When you use the probe to couple energy out of a cavity, the probe acts as a receiving antenna. Figure 80 illustrates this comparison between probes and antennas.

Figure 80. Probe Coupling Compared to Antennas.



b. The receiving antenna in Part A of Figure 80 is picking up the radiated electromagnetic waves of the transmitting antenna. The probe in Part B of Figure 80 is used to either pick up energy from the oscillating cavity or excite the cavity. You place the probe in the area of maximum electric field to transfer maximum energy. If you move the probe away from the maximum electric field, or shorten it, there is less transfer of energy.

c. You know there is maximum voltage in the area of maximum electric field. And, the area of maximum voltage has maximum impedance and minimum current. We say then, that probe coupling is characterized by the following:

(1) High voltage.

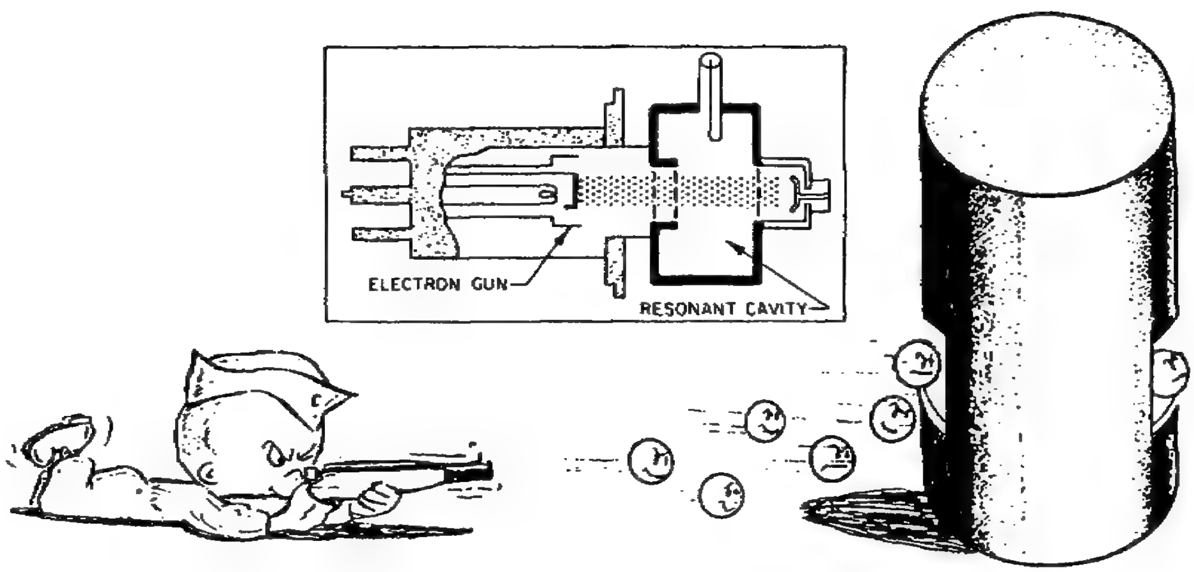
(2) High impedance.

(3) Low current.

23. Slot coupling.

a. Slot coupling (sometimes called electron coupling) is used when we need only a small amount of coupling. In this method, the stream of electrons (or the electromagnetic field) is fed through a slot in the cavity (Figure 81). When used to couple energy into the cavity, the slot is placed at the point of maximum electric field.

Figure 81. A Resonant Cavity Using Slot Coupling.



b. When used to couple energy out of the cavity, the slot is placed at the point of maximum magnetic field, just as we did with loop coupling. Slot coupling therefore, has the same characteristics as loop coupling. They are as follows:

(1) High current.

(2) Low voltage.

(3) Low impedance.

24. Summary of coupling methods.

a. The three principle means of coupling energy into or out of a resonant cavity are called loop coupling, probe coupling, and slot coupling.

b. The loop is placed in the area of maximum magnetic field.

c. The probe is placed in the area of maximum electric field.

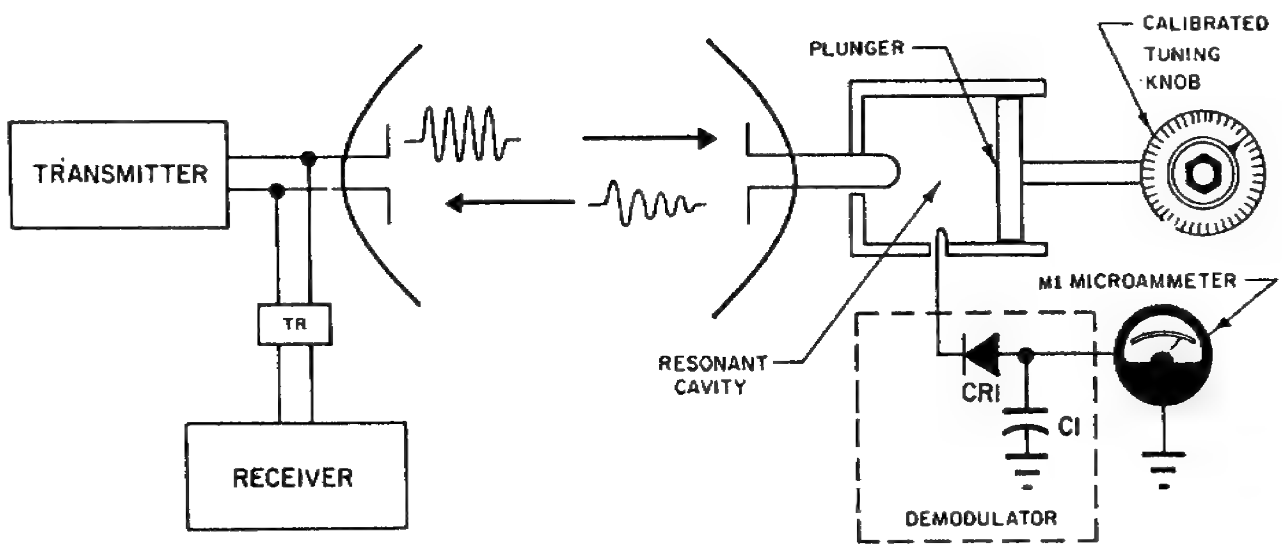
d. When coupling energy out of the cavity, the slot is placed in the area of maximum magnetic field, but when coupling energy into the cavity, the slot is placed in the area of maximum electric field.

e. So far, you have learned how a resonant cavity works, and why they are used at microwave frequencies. Now, let's look at some practical applications that you will run into as a repairman.

25. A resonant cavity is used in test equipment.

a. A resonant cavity is used as a piece of radar test equipment called an echo box. An echo box consists mainly of a high Q resonant cavity that oscillates when excited by a radar pulse. The energy picked up is used to check performance of the radar set. A typical echo box setup is shown in Figure 82.

Figure 82. Echo Box as Used to Check Radar Set Performance.



b. The echo box in Figure 82 has more than just a resonant cavity. In addition to the cavity, it contains a demodulator circuit, a microammeter, and a knob with a calibrated dial.

c. The demodulator circuit consists of crystal diode CR1 and capacitor C1. The crystal diode rectifies the RF energy. The capacitor shunts the RF component to ground and filters the pulsating DC. Therefore, when the cavity is excited, DC flows though microammeter M1.

d. The resonant cavity is plunger-tuned with a knob that has a calibrated dial. The dial indicates the frequency to which the cavity is tuned.

26. How you use the echo box.

a. Using the echo box, you can determine if the radar set is operating at the correct frequency. Here's how:

(1) Adjust the tuning dial until the meter gives a maximum reading. You will get a maximum reading only when the echo box is tuned to the radar frequency.

(2) Read the frequency indicated by the calibrated dial. The dial setting indicates the radar transmitter frequency.

b. So, you see how important the echo box is in determining if the radar transmitter is operating at its assigned frequency.

c. The echo box is also used to check transmitter power and the receiver sensitivity. Now let's look at some other applications of resonant cavities.

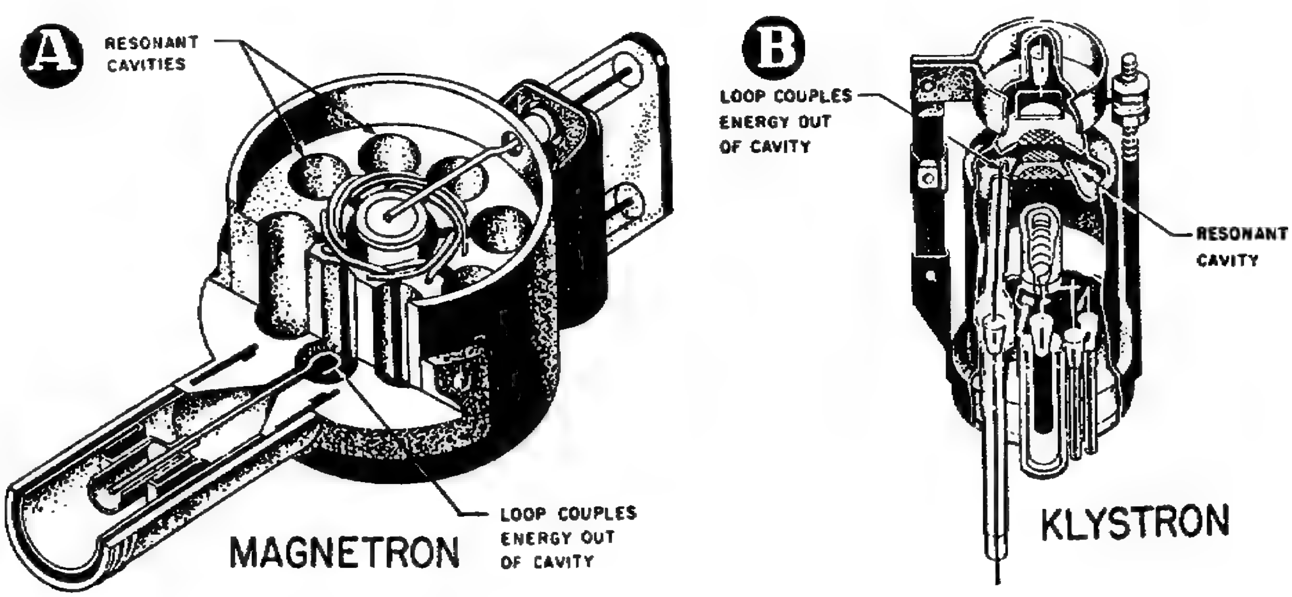
27. A magnetron contains resonant cavities.

a. A magnetron is an electronic component used as a microwave generator. A magnetron is basically a diode tube containing a series of resonant cavities which are excited by a rectangular pulse. The oscillating frequency of the magnetron depends upon the size of the cavities. Part A of Figure 83 is a picture of a typical magnetron with its interior exposed.

b. You see in Part A of Figure 83, the eight cylindrical resonant cavities that determine the magnetron oscillating frequency. Plungers in the cavities are used to tune the magnetron to the desired frequency. Notice also the loop in the cavity on the left-hand side of the magnetron. The loop couples energy from the magnetron to the transmission line that feeds the antenna. You will learn more about magnetrons a little later in the course.

c. The local oscillator in a radar receiver is also a microwave generator that has a resonant cavity. The tube in this circuit is called a klystron.

Figure 83. Interior of Typical Magnetron and Klystron Tube.



28. Klystrons have resonant cavities.

Klystrons are similar to magnetrons in that they also use resonant cavities to produce microwave oscillations. Part B of Figure 83 shows the cavity of a typical klystron tube. One wall of the cavity is a diaphragm. You adjust the diaphragm to tune the cavity to the desired oscillator frequency. Notice the loop in the klystron cavity. Like the magnetron, the klystron uses loop coupling. You will learn more about klystron later on.

29. Final summary.

You have learned in this lesson sheet why we use resonant cavities and some of their uses. The most important points to remember about resonant cavities are as follows:

(1) A resonant cavity is used as a tuned circuit at microwave frequencies.

(2) A resonant cavity consists of a hollow chamber with conducting walls.

(3) Resonant cavities have very low resistance and therefore have a very high Q.

(4) Resonant cavities are made in various shapes, such as square, rectangular, toroidal (doughnut shaped), and cylindrical.

(5) The energy in a resonant cavity is contained in its electric (E) and magnetic (H) fields.

(6) The combination of E and H fields is called the electromagnetic field.

(7) Four principle methods of tuning a resonant cavity are with a plunger, a diaphragm, a screw, or a paddle.

(8) Three principle methods of coupling energy to or from a resonant cavity are with a loop, a probe, or a slot.

(9) Resonant cavities determine the resonant frequency of echo boxes, magnetrons, and klystrons.

Learning Event 2:
MAGNETRONS.

1. General.

a. A radar transmitter is made up of two major units, the modulator and the magnetron. The modulator forms the radar pulse and turns the RF carrier on and off. In fact, the modulator acts just like a switch and may therefore be thought of as a keyer.

b. You have already learned how the modulator develops a radar pulse of the correct width and amplitude. Now you will learn how this pulse helps to generate an RF carrier. After this, the next step is to direct the carrier out into space and search for targets.

c. A different method is used in generating the carrier frequency in a radar set than is used in a radio set. The oscillator in a radio transmitter employs many units to generate the RF, but a radar set uses only one oscillator unit, the magnetron. If anything goes wrong with the magnetron, causing it to stop working, the radar set cannot be used. That's why the magnetron is so vital to radar set operation. And that's why you must know how to maintain the magnetron properly.

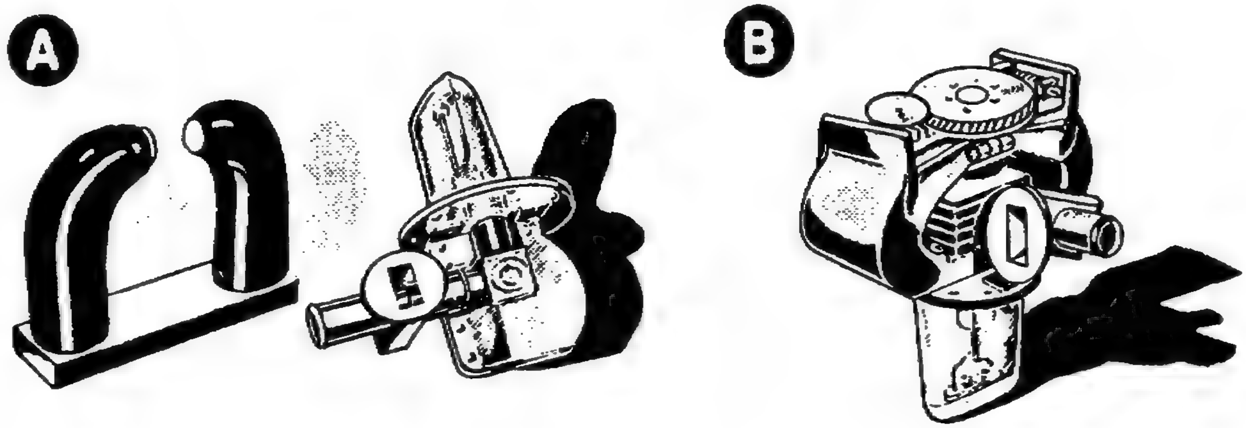
d. In the first part of this lesson, you will see how a magnetron is constructed and learn how it works. Then you will learn why the amount of voltage and strength of the magnetic field applied to a magnetron must always be correct. Finally, you will learn how to take care of magnetrons, what troubles they may develop, and how to make some magnetron checks.

2. Construction of a magnetron.

a. Figure 84 shows two types of magnetrons. You already know that a magnetron consists of a diode and a magnet. Sometimes the magnet is separate from the tube as in Part A of Figure 84. When the magnet is part of the tube as in Part B of Figure 84, it is called a packaged magnetron.

b. Some magnetrons, like the one shown in Part A of Figure 84, oscillate at only a fixed frequency. The magnetron in Part B of Figure 84 is a tunable type which you tune by means of the two gears on top of the tube.

Figure 84. Two Types of Magnetrons.

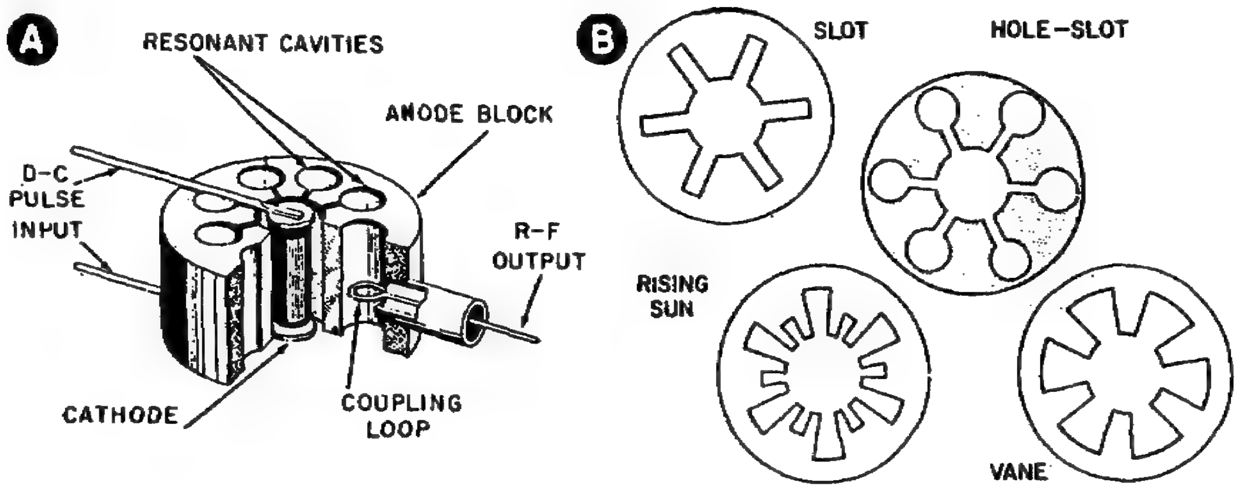


c. The magnetron tube itself consists of a cathode, a filament to heat the cathode, and an anode (Part A of Figure 85). The indirectly heated cathode is oxide-coated. The anode is made from either a solid or laminated copper block.

d. Part B of Figure 85 shows that the magnetron anodes contain either rectangular slots, triangular slots, or a combination of holes and slots. These slots or combinations of holes and slots are actually resonant cavities. When the slots are rectangular, the resonant cavities are called slot resonators. When the slots are triangular, the resonant cavities are called vane resonators. If alternate vanes are two different sizes, they are called rising sun resonators. And when the resonant cavities consist of a circular hole and a slot, they are simply called hole and slot resonators.

e. All magnetrons have between 6 and 18 (always an even number) cavities that are electrically in parallel with each other no matter what their shape. This means the individual inductances and capacitances of each cavity are connected in parallel with each other. Therefore, the resonant frequency of the magnetron is the resonant frequency of an individual cavity.

Figure 85. Internal View of the Resonant Cavity Magnetron.



f. The sections of the anode block that are between the cavities are called segments, and the space between the cathode and anode block is called the interaction space. It is in this space that the high-voltage, DC pulse from the modulator is converted into the RF carrier.

3. How energy is coupled out of a magnetron.

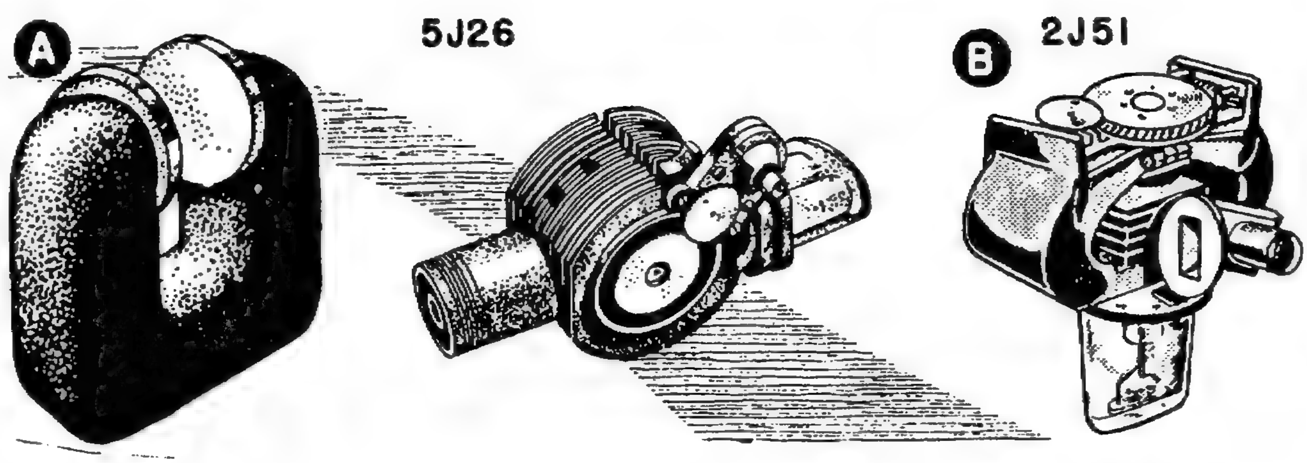
Notice the coupling loop in Part A of Figure 85. It is used to couple energy out of the magnetron. You might think at first that there should be a loop in each cavity. But, remember that the cavities are all in parallel, and when we couple energy from one cavity, we are actually coupling energy from all the cavities. Sometimes, instead of coupling the RF energy out of the magnetron with a loop, we just couple it out through a Slot. As with loop coupling, it is necessary to have a slot in only one cavity.

4. The outside construction of a magnetron.

a. Part A of Figure 86 shows the outside of the 5J26 magnetron and its magnet. The 5J26 is used in radar set AN/TPS-1D. You can see that the magnet is a permanent horseshoe type and is separate from the tube. Most magnetron magnets are made of ALNICO, which is a combination of aluminum, nickel, and iron. ALNICO is used for permanent magnets because it holds its magnetism indefinitely.

b. The 5J26 magnetron oscillates at frequencies between 1220 and 1350 megahertz. You tune it to the correct frequency using the two gears on the side of the magnetron. The gears are coupled to tuning rings inside the tube. These rings are moved up and down in grooves in the cavity segments to tune the cavities.

Figure 86. Outside View of Typical Magnetrons.



c. The RF energy from the 5J26 is coupled out by means of rigid coaxial line. You can see the coaxial connector on the left side of the magnetron. Sometimes waveguide is used to couple the energy out of a magnetron instead of coaxial line. It all depends on the frequency of the RF carrier. Waveguide is used when the frequency of the RF carrier is above 3000 megahertz.

d. Notice that the construction around the tube consists of many metal fins. These are cooling fins that help dissipate the heat generated by the high-power RF inside the tube. You will find that most magnetrons have cooling fins because the peak power generated inside may be anywhere from a few kilowatts to several megawatts.

e. Finally, look at the glass enclosure on the right-hand side of the 5J26 magnetron. The glass insulates the long filament leads from the chassis. The leads must be long so that they will dissipate the heat generated by the large current flow through the magnetron when it is oscillating. The current flow through a magnetron may be anywhere from a few amps to more than 100 amps.

f. Now, look at the 2J51 magnetron shown in Part B of Figure 86. You can see that the magnet for the 2J51 is part of the magnetron proper. So the 2J51 is called a packaged magnetron. Packaged magnetrons have an advantage over those having separate magnets in that they use a smaller magnet for a given field strength. There is no air gap between the pole pieces, so the magnetic lines of force are more concentrated.

g. Another difference you will notice is that the 2J51 magnetron uses waveguide instead of rigid coaxial line to couple out the RF energy. The reason is that the 2J51 oscillates at frequencies between 8500 and 9600 megahertz.

5. Brief review on magnetron construction.

a. A magnetron is a microwave oscillator that consists of a diode and a magnet.

b. The magnet is either part of the magnetron proper (packaged magnetron) or is separate.

c. The diode section of the magnetron consists of a cathode, a filament to heat the cathode, and an anode.

d. The cathode is oxide-coated and is indirectly heated by the filament.

e. The anode is a circular copper block containing six to eighteen resonant cavities.

f. Magnetrons use loop coupling or slot coupling.

g. RF energy is coupled out of the magnetron by coaxial line or waveguide.

h. The long filament leads of the magnetron are insulated from the chassis by a glass enclosure.

i. Now that you have seen typical magnetrons, let's find out how they work. You are already familiar with other types of oscillators, so we will start by comparing these other types with magnetrons. This way you will get a better idea of magnetron operation.

6. Comparing magnetrons with other oscillators.

A magnetron is like any oscillator in that it generates an alternating current at some particular frequency. Magnetrons differ from other oscillators in that their output

frequency (and usually their peak power) is very high. A magnetron oscillator is actually a tube within a magnet. Even though magnetrons differ physically from other types of oscillators, they have the same basic requirements of a tuned circuit, tuned circuit excitation, and regeneration.

7. All oscillators must have a tuned circuit.

All oscillators have a tuned or resonant circuit that determines the oscillating frequency. In most applications at frequencies below 500 megahertz, the tuned circuit is a coil and capacitor combination. At frequencies between 500 megahertz and 1000 megahertz, the tuned circuit is usually a section of transmission line. At frequencies above 1000 megahertz the tuned circuit used most often is a resonant cavity. Most magnetrons oscillate at frequencies above 1000 megahertz, and therefore they use resonant cavities as tuned circuits.

8. All oscillator tuned circuits must be excited.

You know that an oscillator tuned circuit must be excited. That is, it must have some energy applied to it to start oscillations. For example, the coil and capacitor tuned circuit used with an ordinary vacuum tube oscillator is excited by a surge of current. A tuned circuit made of a section of transmission line is usually excited the same way. The resonant cavities of a magnetron oscillator, however, are excited by the fields built up by current flowing in their walls. You have already seen in a previous lesson how a resonant cavity is shock-excited by an electromagnetic field. Well, magnetron cavities are excited in a similar manner.

9. All oscillators need regeneration.

a. One more requirement of an oscillator is regeneration. This means simply that we must reinforce the energy generated, or it will die out. Ordinary vacuum tube oscillators use positive feedback in which some of the output energy is fed back in phase with the input energy. The energy fed back adds to the input and keeps the oscillator working. This happens because the energy feedback is greater than the energy being lost.

b. A magnetron also needs regeneration to continue oscillating after it has been excited. Energy generated in the resonant cavities is reinforced by energy given off by electrons emitted from the magnetron cathode. The electrons add their energy in phase with the oscillating energy. Because the energy added is greater than the energy lost, oscillations don't die out.

c. Later in this lesson, you will learn exactly how a magnetron meets these three oscillator requirements of a tuned circuit, tuned circuit excitation, and regeneration.

10. How a magnetron works.

You know from examining the construction of a magnetron that it consists of a diode and permanent magnet. If we combine the qualities of a permanent magnet with the operation of a diode, you will get a good idea of how a magnetron works. We will start with the operation of a diode, next the magnet, and then put the two together.

11. Electron flow in diode tube.

a. You know that a diode tube has two main elements: the cathode and the anode (plate). The cathode is coated with a chemical substance such as thorium oxide, which emits electrons when heated. Electrons flow from the hot cathode to the anode only when the anode is at positive potential with respect to the cathode. The circuit action for ordinary diodes and magnetron diodes is the same, but the circuit arrangement is slightly different. The two arrangements are compared below.

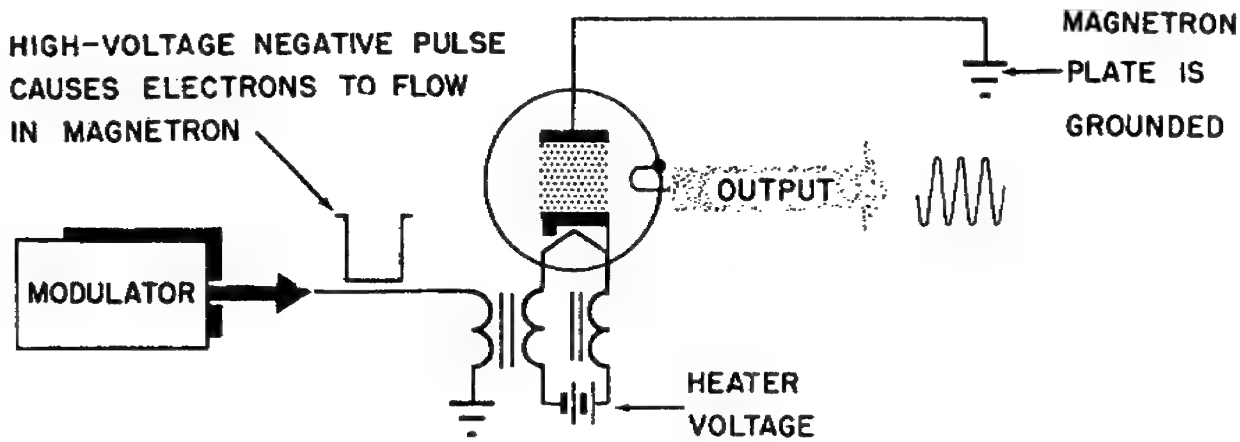
(1) In ordinary diode tube circuits, the cathode is connected to negative voltage and is grounded. The anode is then connected to the positive terminal of the same DC source.

(2) In magnetron diode circuits, the cathode is still connected to negative voltage and the plate to positive voltage, but the plate is grounded instead of the cathode.

b. The diode circuit action, of course, is still exactly the same. Electrons flow from the heated cathode to the positive plate. Grounding the plate instead of the cathode does not affect the diode circuit action.

c. The magnetron anode actually forms the metal envelope of the tube. So, when the magnetron is bolted to a radar chassis, the anode becomes grounded. Electrons flow when the high voltage DC pulse is applied to the cathode (Figure 87). Grounding the anode this way prevents a shock hazard when the high-voltage pulse is applied to the magnetron.

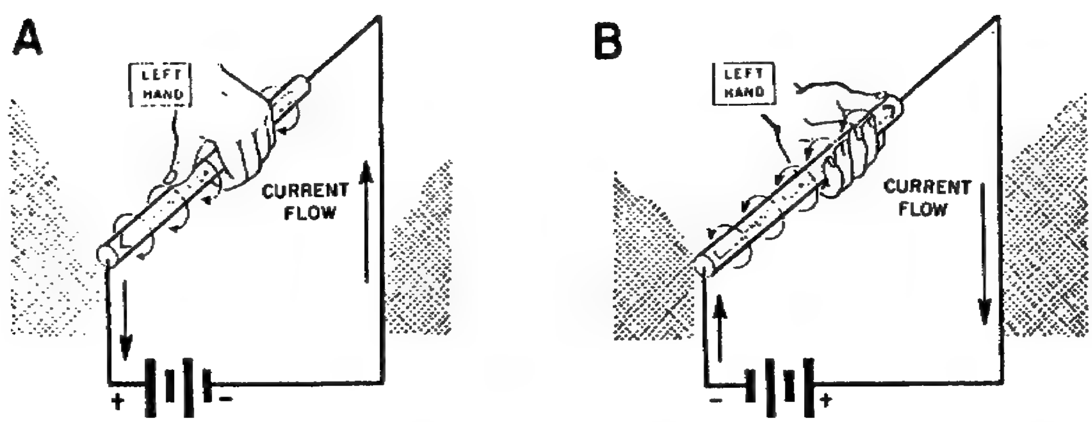
Figure 87. Negative Pulse from Modulator makes Electrons Flow in Magnetron.



12. Reaction of one magnetic field on another magnetic field.

a. Whenever electrons flow, a magnetic field surrounds the flow of electrons. Remember the "left-hand" rule? The rule states that if you point the thumb of your left hand in the direction of the electron flow, your fingers point in the direction that the magnetic field travels around the conductor (Figure 88).

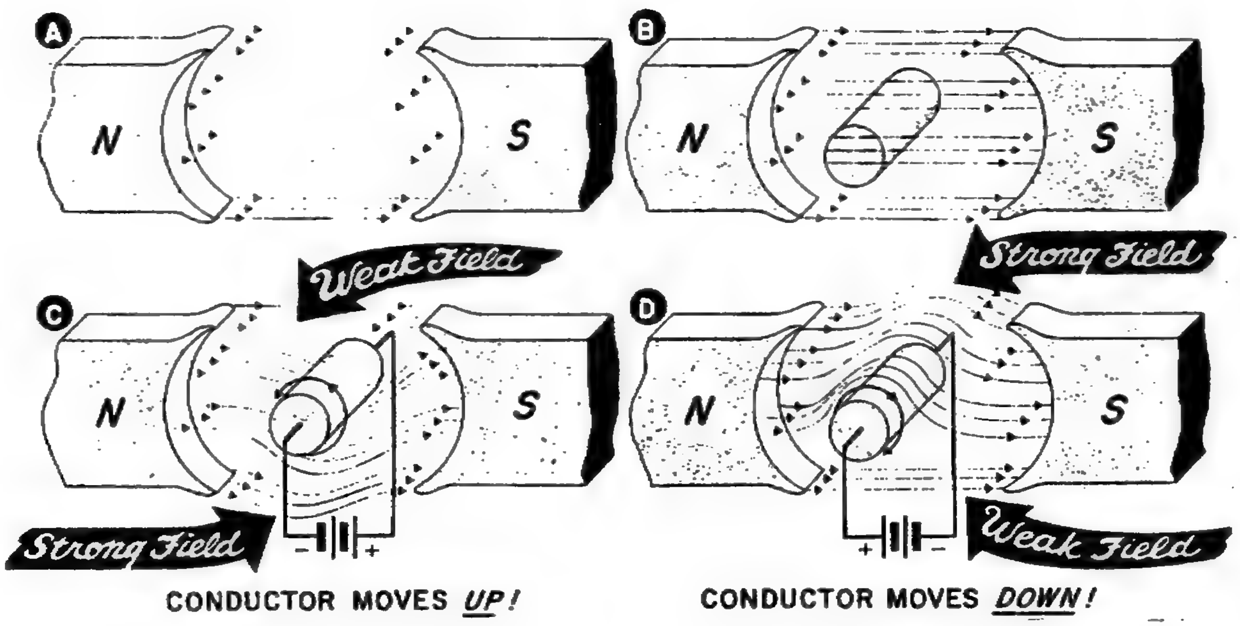
Figure 88. Direction Magnetic Lines of Force Travel Around a Conductor.



b. You also saw in a previous lesson what happens to a conductor when it is placed between the poles of a permanent magnet. The conductor moves because of the interaction between the two magnetic fields. Figure 89 shows you why the conductor moves.

c. The field of the magnet adds to the conductor magnetic field on one side and cancels the conductor magnetic field on the other side. The combination of a weak field above the conductor and a strong field below the conductor makes the conductor move up. In other words, the stronger field below pushes the conductor into the weaker field above the conductor.

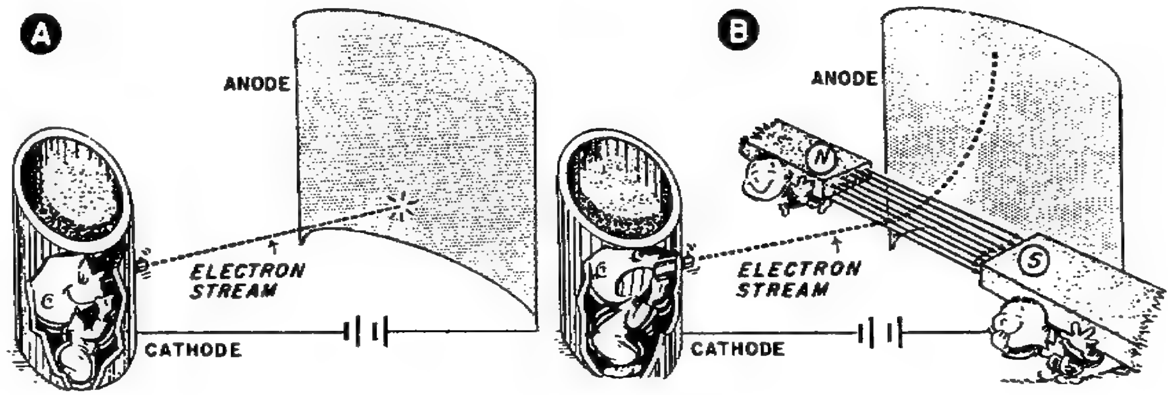
Figure 89. How a Current-Carrying Conductor Moves in a Magnetic Field.



13. A permanent magnet can also move electrons in a diode.

a. Notice the cartoonized version of diode action shown in Part A of Figure 90. It shows how electrons emitted from the hot cathode go directly to the anode when the anode is positive with respect to the cathode.

Figure 90. How a Permanent Magnet Moves Electrons in a Diode.

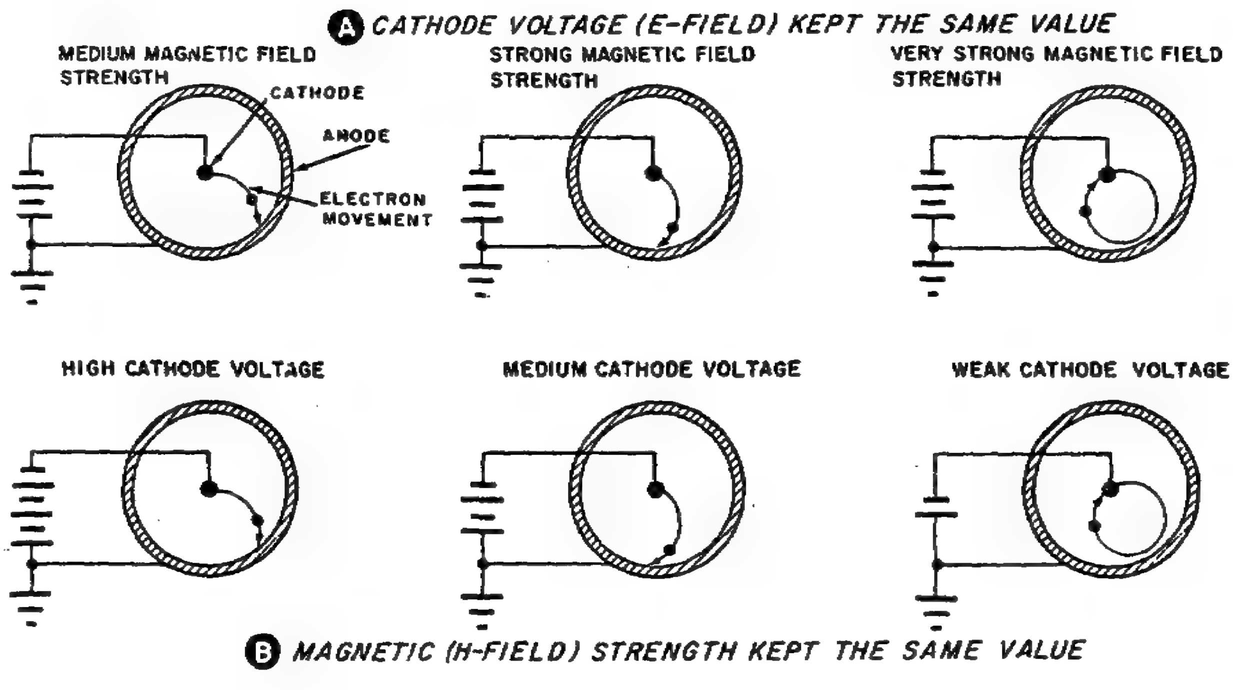


b. Now notice what happens to the electron flow when we add a permanent magnet to the diode as in Part B of Figure 90. Instead of traveling to the plate in a straight path, the electrons take a curved path. Why does the permanent magnet have this effect on electron flow? Well, you remember how a permanent magnet moves a wire that has electrons flowing through it. The wire moves because the magnetic field around the electrons inside the wire interact with the magnetic field of the magnet. It's the same thing here, the electrons traveling through the space between the cathode and plate have the same kind of magnetic field around them as the electrons moving through a wire. Therefore, the permanent magnet affects the electrons moving from cathode to plate in the same way. Thus, the permanent magnet makes the electrons move in a curved path toward the plate.

14. Strength of magnet and cathode voltage determine electron path.

Now let's see what happens if we use different size magnets and different values of cathode voltage. First we will keep the same voltage on the cathode and vary the magnetic field strength. You can see in Part A of Figure 91 that the greater the force of the magnet, the greater is the arc in which electrons travel from cathode to anode. In fact, if the magnetic field is too strong, the electrons double back to the cathode and never reach the anode.

Figure 91. How the Voltage and Magnetic Field Affect Electron Movement.



15. Now change the cathode voltage.

a. Now, let's use the same magnet, but change the cathode voltage. You can see in Part B of Figure 91 that as we lower the cathode voltage, the electrons take a more curved route to the anode. In fact, if the cathode voltage is too low, the electrons never reach the anode.

b. From this you can see that the cathode voltage and magnetic field strength work hand in hand. Increasing the magnetic force has the same effect as lowering the cathode voltage. And by keeping one steady and varying the other we can change the path of the electrons.

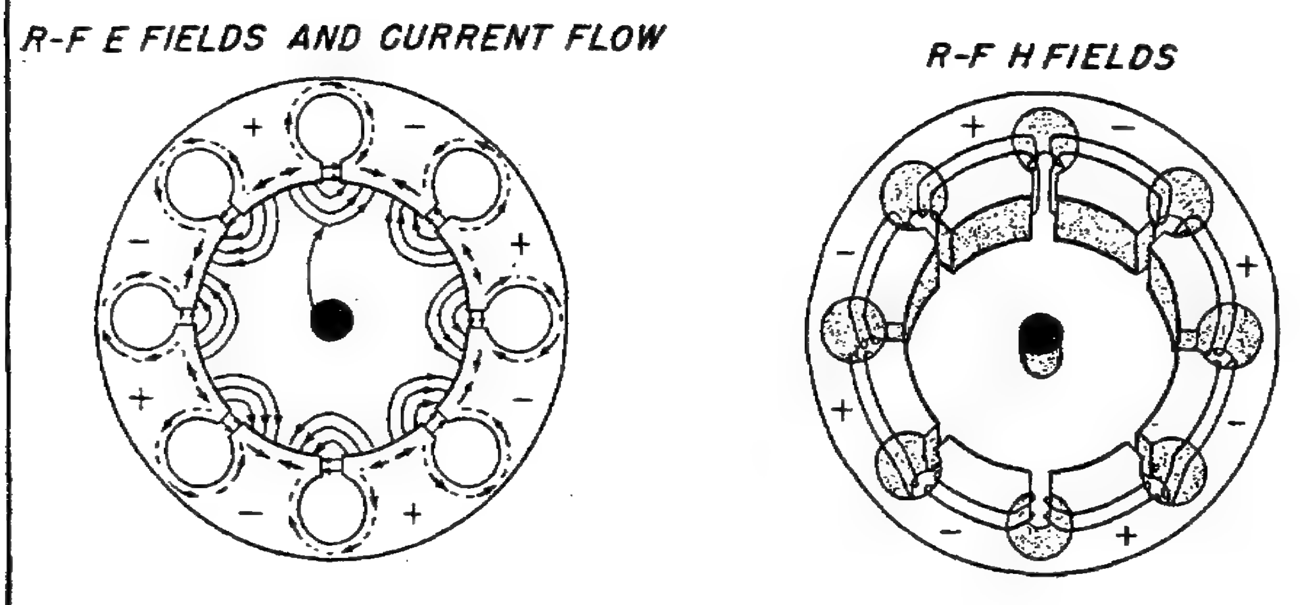
c. In practice there is only one correct combination of magnetic field strength and cathode voltage that gives the desired output from the magnetron oscillator. The correct combination is one that causes the electrons to reach the anode only after they pass by some of the resonant cavities in the magnetron.

16. Electrons that strike the anode excite the cavities.

a. You know that an oscillator tuned circuit must be excited. This really means that energy must be introduced into the tuned circuit so that it can vary at the resonant frequency of the tuned circuit. The method of exciting a magnetron tuned circuit is shown in Figure 92. There you see the direction of current flow, the RF E fields, and RF H fields.

b. The electrons emitted from the cathode take a curved path in traveling to the anode. The first electrons that strike the anode block cause current to flow in the anode, and the RF fields are built up within the cavities and interaction space. The fields then vary at the natural resonant frequency of the cavities. You have already seen this method of excitation in resonant cavities. When cavities are excited like this we say they are shock-excited.

Figure 92. How Magnetron Cavities are Excited.



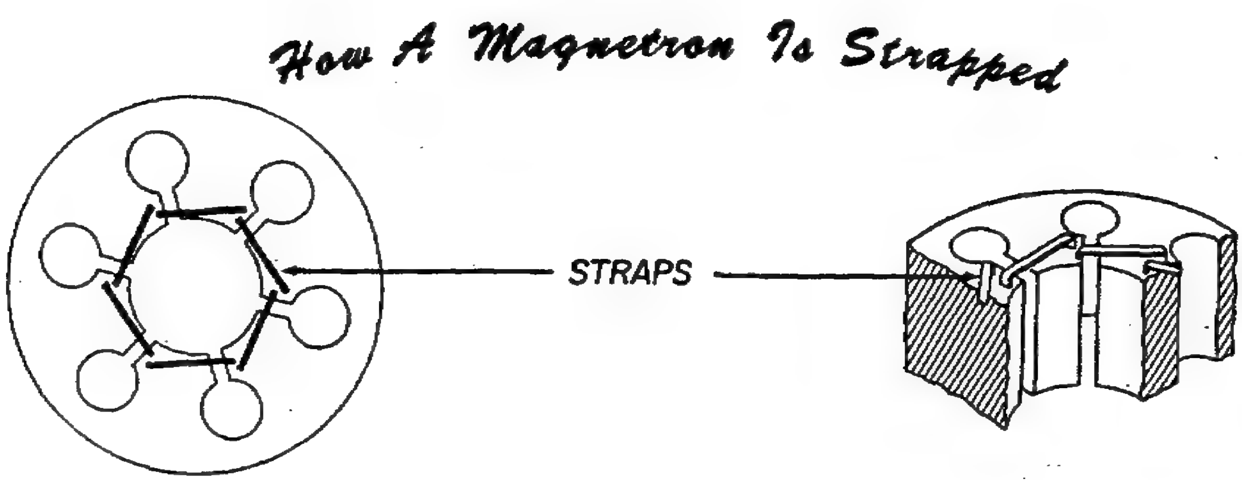
c. Another thing you learned when studying resonant cavities was that the fields may take different patterns in the cavities. These patterns are called modes of operation. There are many modes of operation possible in a magnetron, but only one mode, called the pi mode, gives the most power output and the highest efficiency. The fields for pi mode operation are shown in Figure 92.

d. We call this manner of operation the pi mode because the RF fields oscillate in such a way that each segment is 180 degrees out of phase. In other words, every other segment is positive and the ones in between are negative. (That's why there are always an even number of cavities in a magnetron.) One-half cycle later they all reverse their polarity.

17. Segments are strapped to ensure correct polarity.

a. It is because every other segment must be the same polarity that magnetrons are sometimes strapped. A strapped magnetron is one in which every other segment is connected together with a wire or bar (called a strap) as in Figure 93. The straps ensure that there is a good connection (increased coupling) between alternate segments and thus help the magnetron oscillate in the pi mode. "Rising Sun" type magnetrons are not strapped because the vanes are two different sizes. Every other vane is larger than the ones in between. This has the same effect as trapping the "hole and slot" type magnetrons.

Figure 93. Straps Help Magnetron to Oscillate in pi Mode.

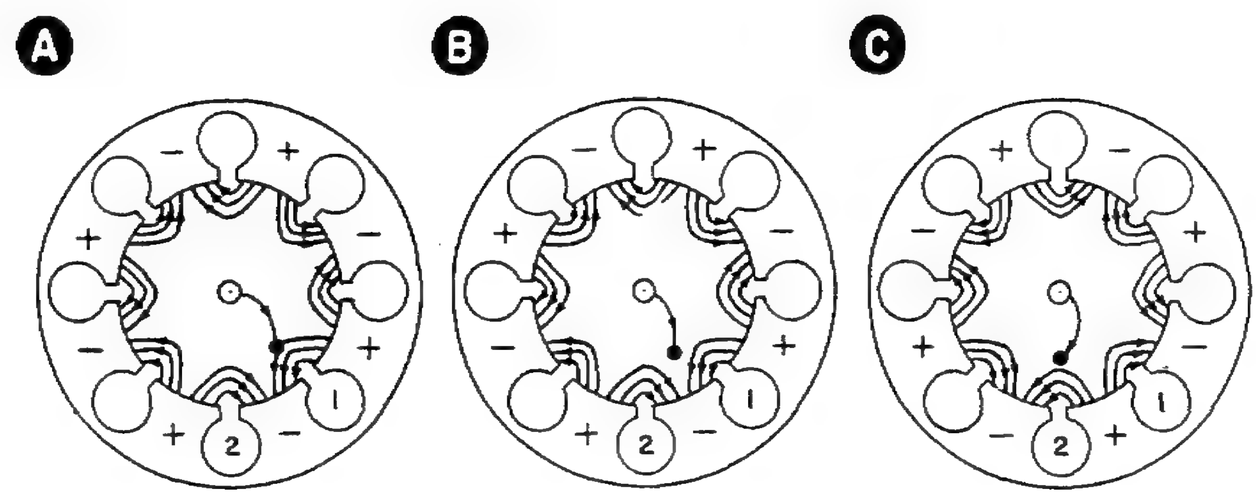


b. The energy oscillating within the magnetron cavities must be reinforced or the oscillations will die out. This brings us to the reason why the electrons are made to curve and pass by some cavities on their way to the anode block.

18. When electrons pass cavities at the right time, they sustain oscillations.

a. Figure 94 shows how the electrons keep the magnetron oscillating. When an electron arrives at a cavity gap (Part A of Figure 94), it hits the cavity RF field. If the electron hits the field when the field is at peak value, and is also moving in the same direction as the electron, the electron is slowed down. As the electron slows down, it gives up some of its energy to the RF field. The added energy keeps the field from dying out. This means that as long as the electrons hit the fields at the right time, the cavities keep oscillating.

Figure 94. How the RF Fields are Reinforced.



b. Part B of Figure 94 shows the electron an instant later. Now the electron is out of the RF field and is gaining speed. At the same time, the RF fields are reversing direction. By the time the electron reaches the next cavity (Part C of Figure 94), the fields have reversed. That means the electron reaches the RF field of the next cavity when the field is maximum and in the same direction as the electron. So the same thing happens as before: the electron is slowed down by the field, and gives up some energy to the field. So, you see that as long as the electrons from the cathode hit the RF fields at the right time, oscillations continue.

19. Finally, the electrons reach the anode.

The electrons reach the anode only after they have taken a spiral path and given up some energy to the oscillating RF fields. Some electrons never reach the anode, but instead they return to the cathode. Electrons that return to the cathode are lost. But when they hit the cathode, they cause it to get hotter. Most magnetrons therefore either have their filament voltage turned off or turned down after they have started oscillating If the filament voltage were kept at the full starting value, the combination of filament voltage heat and the heat from the returned electrons would damage the tube.

20. Summarizing electron movement.

a. Electrons strike the anode block and shock excite the resonant cavities.

b. The RF fields in the cavities oscillate in such a way that alternate anode segments are of the same polarity and 180 degrees out of phase with their neighboring cavities.

c. Then the electrons pass the RF fields in phase and add their energy to the fields.

d. The fields keep oscillating until the voltage applied to the cathode is removed and the electrons stop flowing.

e. These four steps briefly state the operation of the magnetron. The most critical part of the operation is getting the electrons to pass the RI fields at the right time to keep the magnetron oscillating.

21. Cathode voltage and magnetic field make electrons pass at the right time.

a. You have already seen how the voltage across the diode and the magnetic field of the magnet affect the electrons. The correct values of voltage and magnetic force make the electrons travel in the right path. That path is the one where the electrons pass the RF fields so as to add their energy to them. If they don't add their energy in the right way, the magnetron will not oscillate at all, or it will operate erratically. This means then if the voltage or magnetic field change from the correct values, one of the following trouble symptoms will occur:

(1) The magnetron will not oscillate at all.

(2) The magnetron will oscillate at the wrong frequency.

(3) The magnetron will oscillate at several different frequencies.

(4) The magnetron will have very little output power.

b. Naturally, any of these things will reduce the efficiency of the radar set and may even take it out of operation. That's why you must take great care when handling a magnetron and its magnet. We will discuss the care and handling of magnetrons after this summary of magnetron operation.

22. Summary of magnetron operation.

a. Magnetron anodes are grounded to prevent a high-voltage hazard.

b. Electrons flow in the magnetron when the heated cathode is made highly negative with respect to the anode.

c. Electrons emitted from the cathode travel in an arc because of the powerful magnetic field at right angles to them.

d. The electrons excite the resonant cavities of the magnetron and set up RF fields that oscillate at the cavity resonant frequency.

e. The electrons keep adding energy to the cavity RF fields, and oscillations continue until the negative voltage is removed from the cathode.

f. Values of cathode voltage and magnetic field strength must be correct for the magnetron to operate properly.

g. Remember that it is the field of the permanent magnet that keeps the electrons from rushing directly to the plate. If there is no field or a very weak field, the plate will be bombarded and the tube may be destroyed at once. Even if the field is only slightly weak, it may not destroy the tube, but it will probably cause erratic operation and reduce the life of the magnetron.

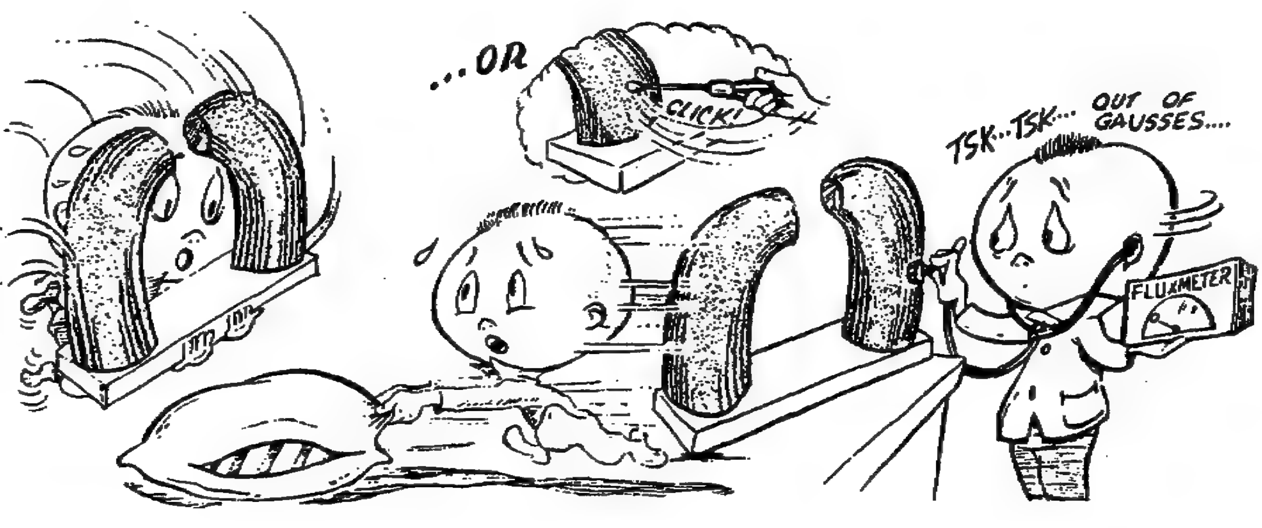
23. Care and handling of magnetron magnets.

Although a magnetron is very rugged electrically, it should be handled with a great deal of care. The same holds true for its magnet. The magnet is not a toy, so resist the temptation to play with it. Keep in mind the following precautions when handling magnetron magnets.

a. Do not drop magnets (Figure 95).

Do not drop, hit, or jar (even slightly) a magnet because it will greatly reduce the field strength. For example, if you drop the magnet or tap it once with a screwdriver, its strength may be reduced by 50 gausses. Since many magnetron magnets have an operating field strength of about 2,000 gausses, just a few taps will lower their field strength enough to prevent proper operation.

Figure 95. Never Drop or Hit a Magnet.



b. Keep metal tools away from magnets.

Magnetron magnets are very powerful and attract metal tools even when many inches away. Use nonmagnetic tools at all times when working near magnets. But, if you must work near the magnet with a screwdriver, pliers, or any metal instrument, be very careful. Get a firm grip on the tool you are using, or it will be pulled to the magnet.

c. Do not wear a wristwatch near magnets.

Another thing to remember when working close to a magnet is to remove your watch. The strong field around the magnet may stop it from running. Even if you have a watch that is not affected by the field, it may be drawn to the magnet and broken.

d. Cover the magnet when drilling or filing.

If you must drill or file near a magnet, completely cover it with a cloth or tape. This precaution will prevent the filings from adhering to the magnet.

e. Store magnets with their keepers in place.

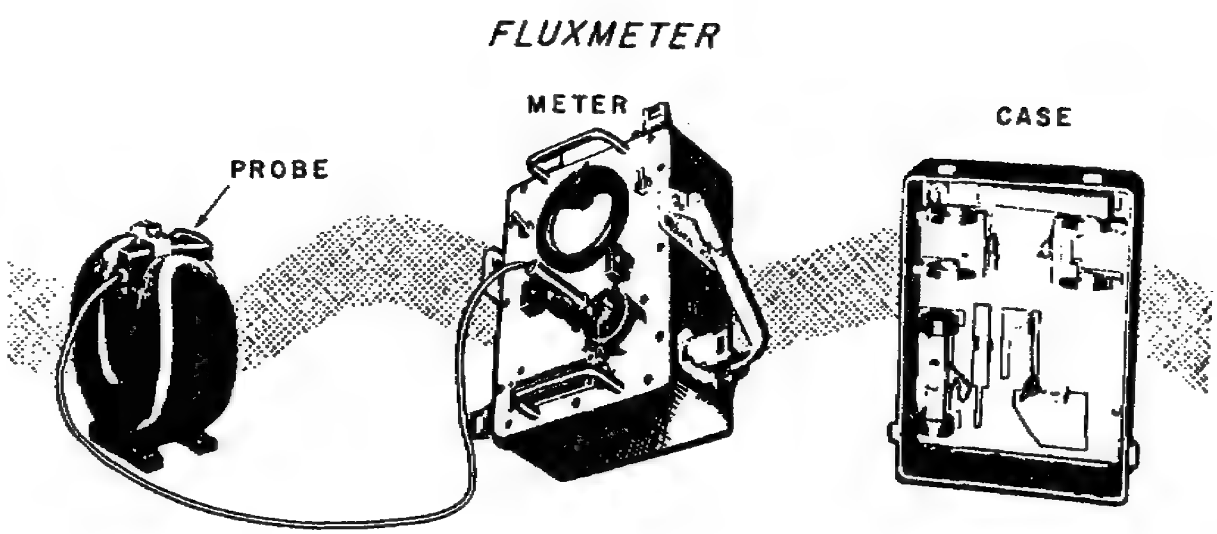
(1) Finally, when you store magnets, always put their keeper in place. The keeper concentrates the field between the poles and helps the magnet retain its strength. Also, if a magnet becomes weak, you can restore its strength somewhat by inserting and removing the keeper five or six times.

(2) If you have two or more magnets stored in the same area, be sure they are separated by at least six inches. This separation prevents interaction of the fields, which could cause loss of field strength. If there is any doubt about the field strength of the magnet, you should measure its strength.

24. Measuring magnet flux.

a. When you are replacing a magnet and are not sure of its strength, measure it with a fluxmeter. In fact, it's a good idea to measure the flux of any new magnet before you put it in the set. You don't know whether or not the magnet has been dropped or tapped before you received it. The only way to be sure it has the correct strength is to measure it with a fluxmeter (Figure 96).

Figure 96. Measuring the Field Strength of a Magnet.



b. A fluxmeter is a piece of test equipment that measures the strength of a magnet field. It consists of two main parts:

(1) A probe that you insert between the pole pieces of the magnet you are testing.

(2) A meter that indicates the strength of the field in gausses.

c. You will learn more about the fluxmeter later on. Right now remember that it is very easy to check the field strength of a magnet with this meter whether the magnet is out of the set or still in it.

d. This means of course that if you have magnetron trouble and think it's the magnet, all you have to do is measure the magnet to make sure. (Of course, you can't measure the field strength of a packaged magnetron because the tube is permanently attached between the pole pieces.) If the field strength is a lot less then it should be, replace the magnet. If the magnet measures the correct amount, then the trouble is the magnetron, not the magnet.

25. Operating a new magnetron.

a. When you install a new magnetron in a radar set, check its operation carefully because excessive arcing or sparking usually occurs. One cause of arcing is gas that has accumulated in the tube while it has remained idle.

b. When a magnetron arcs, flashes may be seen or heard through the glass seals, and the anode-current meter may fluctuate violently. Arcing shortens the useful life of the magnetron by damaging the cathode. A great deal of current flows and generates a lot of heat. The heat may destroy the tube, or the high current drain may damage the modulator. Therefore, before operating a new magnetron, it must be "aged" to keep arcing to a minimum.

26. How to "age" a new magnetron.

a. Before installing a new magnetron, always break-in the magnetron by carefully following the aging procedure below:

(1) Apply only the filament voltage to the magnetron, and let it warm up for about fifteen minutes.

(2) Apply only a portion of the high voltage to the magnetron.

(3) Listen for arcing within the tube and watch the magnetron current meter. (The meter needle jumps around when the tube arcs.)

(4) Gradually increase the high voltage.

(5) If arcing occurs, turn down the high voltage.

(6) Wait a minute, and start turning the high voltage up again.

(7) Continue this routine until arcing stops.

b. Note that these steps provide only a general outline for aging a magnetron and should be used only when no instructions for the set are available. You should always follow instructions given in the TM for the particular set you're working with.

c. It may take an hour or more before all arcing has stopped and the magnetron has been "cleaned up" (free of gas). Fortunately a magnetron can stand a considerable amount of arcing without any damage, but you should hold it to a minimum. Remember that you hold the high-voltage down to keep the arcing down.

d. Magnetron arcing is normal for new tubes and old tubes that need replacement. There are other more serious magnetron troubles that you will run into. Let's see now what these other troubles are and find out what causes them.

27. Troubleshooting the magnetron.

a. Before troubleshooting, you must know how the equipment operates so you can recognize and analyze trouble symptoms as soon as they occur. After recognizing the trouble symptom, the next step is sectionalization. You sectionalize the trouble by first analyzing and evaluating the symptom. You will find that troubles causing faulty magnetron operation usually occur in the RF and modulator sections of the radar set.

b. When the cause for the magnetron operating at the wrong frequency is in the RF section, we call the trouble magnetron pulling. In other words, the magnetron is actually pulled off its correct oscillating frequency by some bad or mistuned component located somewhere between the magnetron and the antenna or even beyond the antenna.

c. When the cause for faulty magnetron operation is in a unit located ahead of the magnetron (the modulator), we call the trouble magnetron pushing. In other words, the magnetron is actually pushed off its correct oscillating frequency by some bad or mistuned component located somewhere in or before the modulator.

d. Although magnetron pulling is more common than magnetron pushing, either trouble is likely to occur because magnetron operating requirements are so critical.

28. Magnetron pulling.

a. The trouble is called magnetron pulling when the frequency of the magnetron is changed (pulled off frequency) by a mismatch somewhere past the magnetron. That is, the mismatch is either between the magnetron and the antenna, or it's caused by something beyond the antenna. You will recall from a previous lesson, Transmission Lines, that a load must be matched to its generator circuit in order to get maximum power out. This is true also of magnetron loads. The load on a magnetron, of course, consists of all the RF components that follow it, including the antenna. Magnetrons also pull off frequency when the load is changed or mismatched. The amount of frequency change and loss of power depends upon how great is the mismatch.

b. Sometimes the mismatch is slight, and the frequency changes only slightly, and the power output remains almost the same. The radar receiver still picks up signals near the desired operating frequency because of its wide frequency response. But if the mismatch is more than just slight, the frequency will change more, and there will be even less power output. So even if the receiver still picks up echoes, the echoes are weak. In an extreme case, the frequency change may be so great that the receiver will not respond at all to the echoes.

c. You can see then, that anything that changes the magnetron output impedance and causes a mismatch may be very harmful, and may even prevent the radar from functioning.

29. Causes of impedance mismatch between magnetron and antenna.

a. The most common causes of mismatch between the magnetron and the antenna are as follows:

(1) Dirt or moisture in the coaxial line or waveguide.

(2) Dirt or moisture on the antenna.

(3) Coaxial line or waveguide that is bent or dented.

(4) Joints that are not soldered properly.

(5) A defective rotating or coupling joint.

b. Most of these causes of magnetron pulling can be avoided by proper care and preventive maintenance of the radar RF components.

30. Causes of faulty operation beyond the antenna.

a. Now, how about the causes of faulty magnetron operation from something beyond the antenna? At first you might think that all troubles would have to be caused by something actually in the set. That's usually true, but in the case of a radar transmitter, troubles can be caused by something that is not a physical part of the equipment. This happens because anything that changes the impedance of the load also effects the magnetron operation.

b. The usual cause of mismatch from something beyond the antenna is a nearby object. The nearby object may be a building, another radar, a smokestack or anything else close enough to the antenna to change its impedance. These types of mismatch can be avoided by selecting a good site for the radar set.

c. Now, suppose there is no mismatch. The load impedance remains constant at its correct value, but the magnetron is not operating correctly. Then, the trouble is probably magnetron pushing.

31. Magnetron pushing.

a. As stated before, magnetron pushing occurs when the frequency of the magnetron is changed (pushed off frequency) by something before the magnetron. In other words, the trouble is something that changes the current of the magnetron even though the load and magnetic field are at the correct values.

b. The most likely spot to look for the cause of this trouble is in the modulator. Actually most magnetron pushing is caused by an improperly shaped pulse coming from the modulator. When the pulse is not the right shape, the magnetron may oscillate in an undesired mode and at the wrong frequency. As with magnetron pulling, the output power drops and the frequency may change enough to make the receiver useless.

32. Other magnetron troubles.

a. Mode skip. Sometimes a magnetron does not fire (oscillate) every time the pulse is applied to the cathode. This happens when the pulse applied from the modulator isn't powerful enough. Of course when the magnetron doesn't fire, there is no output from the set, so the set receives fewer echoes. This means the set's average power output is reduced, and so is its effectiveness. When the magnetron fails to fire on each pulse, we call the trouble mode skip.

b. Mode jump. If each pulse applied to the magnetron isn't the same shape and amplitude, the magnetron may oscillate in different modes with different frequencies. This defect is called mode jump.

c. Mode shift. Sometimes the magnetron may even change its mode of operation during a pulse, and we call this trouble mode shift.

d. Mode jump and mode skip both result in less power being radiated from the radar set and poor efficiency.

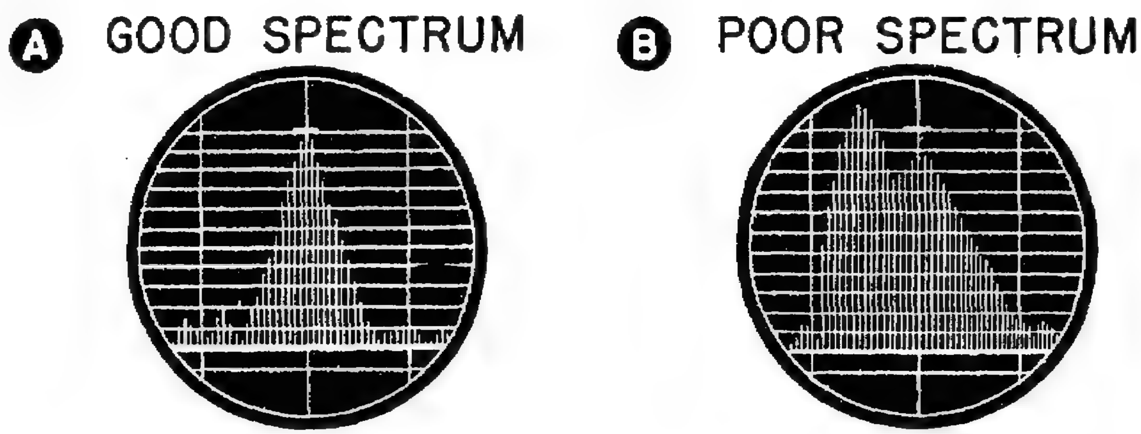
e. When a magnetron is not operating properly, it is not always easy to determine the exact trouble. However, it is easy to determine if the output of the magnetron is correct by using a piece of test equipment called a spectrum analyzer.

33. Spectrum analysis.

a. A radar modulator generates a rectangular pulse that modulates the RF carrier. The rectangular pulse is made up of the fundamental frequency and many harmonics. Each harmonic modulates the carrier frequency producing a sum and difference frequency. These frequencies are called sidebands. Frequencies above the carrier make up the upper sidebands, frequencies below the carrier make up the lower sidebands. Now, if we plot the power of each frequency, we have a spectrum.

b. A spectrum analyzer contains an oscilloscope that shows the magnetron spectrum when the analyzer is connected to the output of a radar transmitter. By checking the spectrum you tell whether or not the magnetron is operating correctly. When the magnetron is operating as it should, and the output of the transmitter is correct, the graph you see on the spectrum analyzer scope looks like the one in Part A of Figure 94. So, if the output of the transmitter looks just like the one shown in Part A or is very similar to it, you know that the magnetron is operating correctly.

Figure 97. Ideal and Very Poor Spectrums.



c. Now look at Part B of Figure 97 which shows a very poor spectrum. A spectrum of this type indicates that the output of the magnetron is not a good rectangular pulse. If the output of the transmitter looks like the spectrum shown in Part B or is distorted in some other way, it means the magnetron is not operating correctly. An incorrect spectrum indicates one of the following troubles:

(1) Magnetron pulling.

(2) Magnetron pushing.

(3) Mode shifting and mode jumping.

(4) Improper pulse width.

d. The spectrum analyzer is a quick means for checking the transmitter. If the radar set is not operating correctly, a spectrum analysis lets you know whether or not the cause of bad operation is in the transmitter. If it is, the next step is to isolate the trouble to a particular stage and component.

34. Final summary.

You have learned in this lesson how a magnetron works, and you have seen some possible causes of magnetron troubles. You realize now that although the magnetron is basically simple, a radar set is useless unless the magnetron is working. Figure 98 lists the main characteristics and operating values of four different magnetrons. This shows at a glance typical values you will work with. As part of the final summary, a glossary of magnetron terms follows Figure 98. Refer to the glossary until you become familiar with these terms.

Figure 98. Typical Operating Values of Magnetrons.

TYPE NUMBER	725A	5J26	2J32	QK324
FREQ RANGE (mc)	9,345-9,405 fixed	1,220-1,350 tunable	2,780-2,820 fixed	15,840-16,160 fixed
BAND	X (3cm)	L (20-75cm)	S (10cm)	K (1cm)
TYPE OF CAVITY	Hole & Slot	Slot	Hole & Slot	Rising Sun
NUMBER OF CAVITIES	12	8	8	18
PEAK-POWER OUTPUT	30kw (min) 70kw (max)	400kw (min) 800kw (max)	250kw (min) 660kw (max)	70kw (min) 100kw (max)
PEAK VOLTAGE	7 to 16 kv	30 kv	10 to 22 kv	22 to 26 kv
PEAK CURRENT	4 to 16 amps	60 amps	30 amps	12 amps
AVERAGE CURRENT	7 ma	42 ma	27 ma	26 ma
MAGNETIC FIELD	5,400 gausses	1,400 gausses	1,900 gausses	8,000 gausses
FILAMENT STARTING VOLTAGE	6.3 VOLTS	23.5 VOLTS	6.3 VOLTS	4.8 VOLTS
FILAMENT RUNNING VOLTAGE	0 to 4.5 VOLTS	16 VOLTS	0 to 6.3 VOLTS	0 VOLTS
LIFE (MINIMUM HOURS)	500 hours	1,000 hours	500 hours	350 hours

35. Glossary of magnetron terms.

a. Magnetron pulling - The frequency of the magnetron changes because of a mismatch between the magnetron and the antenna.

b. Magnetron pushing - The frequency of the magnetron changes because of a faulty modulator.

c. Mode skip - The magnetron does not fire on every pulse.

d. Mode jump - The mode of operation changes from one pulse to the next pulse.

e. Mode shift - The mode of operation changes during the pulse.

f. Packaged magnetron - A magnetron that has its magnet as part of the magnetron proper.

g. Magnetron arcing - Breakdown between the magnetron cathode and anode caused by gasses. Arcing usually occurs in new tubes and in old tubes that need replacement.

h. Magnetron aging - A break-in procedure used to "clean up" gasses in a magnetron.

i. Fluxmeter - A meter that measures the flux density of a magnet in terms of gauss.

j. Spectrum analyzer - A test instrument used to show the distribution of energy contained in the output of a pulsed magnetron.

PRACTICE EXERCISE
(Performance-Oriented)

In each of the following exercises, select the ONE answer that BEST completes the statement or answers the question. Indicate your solution by circling the letter opposite the correct answer in the subcourse booklet.

1. If a single-shorted quarter-wave section of transmission line is compared with two sections connected in parallel, it is found that the two parallel sections have a

   a. larger inductance, a smaller capacitance, and a larger resistance.

   b. smaller inductance, a larger capacitance, and a larger resistance.

   c. smaller inductance, a larger capacitance, and smaller resistance.

   d. larger inductance, a smaller capacitance, and smaller resistance.

2. When comparing the characteristics of parallel-connected, shorted, quarter-wave sections of transmission lines to single quarter-wave sections, it is found that the cavity formed by the parallel section has

   a. a higher resonant frequency and less selectivity than the single section.

   b. A lower resonant frequency and greater selectivity than the single section.

   c. the same resonant frequency but less selectivity than the single section.

   d. the same resonant frequency but greater selectivity than the single section.

3. A resonant cavity that will operate in the PRIMARY mode on a wavelength of 3 centimeters will have length, width, and height respectively of

   a. L = 3 cm, W = 3 cm, H = 6 cm.

   b. L = 6 cm, W = 6 cm, H = 3 cm.

   c. L = 1.5 cm, W = 1.5 cm, H = 1.3 cm.

   d. L = .75 cm, W = .75 cm, H = 3.5 cm.

4. The electric and magnetic fields inside a resonant cavity are always

   a. parallel to each other.

   b. perpendicular to each other.

   c. parallel to the coupling probes.

   d. perpendicular to the coupling probes.

5. The resonant cavity shown in Figure 99 uses slot coupling or electron coupling to insert energy into the cavity. The electric field developed in the cavity will be at its maximum strength

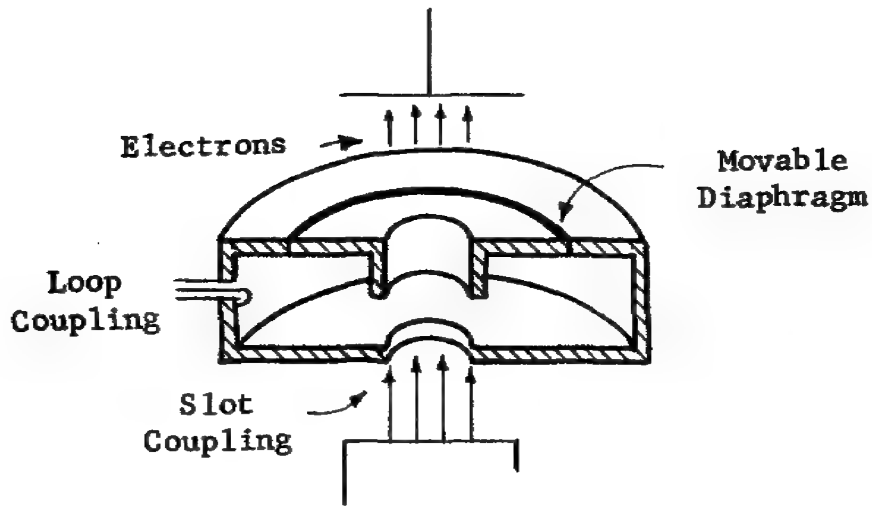
   a. at the center of the cavity, and the magnetic field will be at its maximum strength on the edges of the cavity.

   b. at the center of the cavity, and the magnetic field will be at its minimum strength on the edges of the cavity.

   c. on the edges of the cavity, and the magnetic field will be at its maximum strength in the center of the cavity.

   d. on the edges of the cavity, and the magnetic field will be at its minimum strength in the center of the cavity.

Figure 99. Resonant Cavity.



6. What adjustment can be made to the resonant cavity shown in Figure 99 to cause its resonant frequency to decrease?

   a. Extend the coupling loop further inside the cavity.

   b. Move the diaphragm to decrease the height of the cavity.

   c. Adjust the diaphragm to increase the height of the cavity.

   d. Rotate the coupling loop so that it is perpendicular to the magnetic field.

7. To obtain the maximum output from the resonant cavity shown in Figure 100, the coupling loop should be placed at point

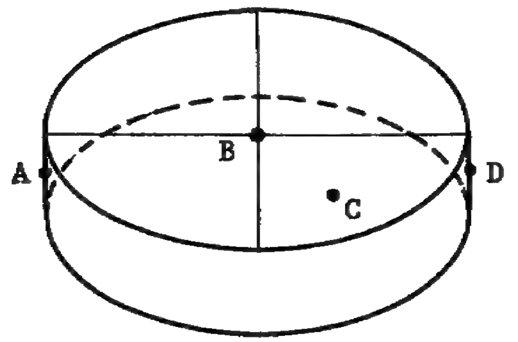
   a. A and parallel to the magnetic field.

   b. B and parallel to the magnetic field.

   c. C and perpendicular to the magnetic field.

   d. D and perpendicular to the magnetic field.

Figure 100. Resonant Cavity Output Connection.



8. The resonant frequency of a cavity resonator may be changed by varying the cavity's electrical or physical size. A cavity resonator's electrical size may be changed by using either a

   a. plunger or a diaphragm.

   b. diaphragm or a screw.

   c. paddle or a plunger.

   d. screw or a paddle.

9. If a probe is to be used to remove energy from a resonant cavity, it should be places at a point that is

   a. parallel to and in the center of the maximum electric field.

   b. parallel to and in the center of the maximum magnetic field.

   c. perpendicular to and in the center of the maximum electric field.

   d. perpendicular to and in the center of the maximum magnetic field.

10. The echo box shown in Figure 82 uses a loop to couple energy from the antenna into the plunger-tuned resonant cavity. The energy is removed from the resonant cavity by a

    a. slot placed in the center of the electric field.

    b. loop placed in the center of the magnetic field.

    c. probe placed in the center of the magnetic field.

    d. probe placed in the center of the electric field.

11. One method of classifying a magnetron is by the type of resonant cavity used in its anode block. The magnetron shown in Figure 101 uses

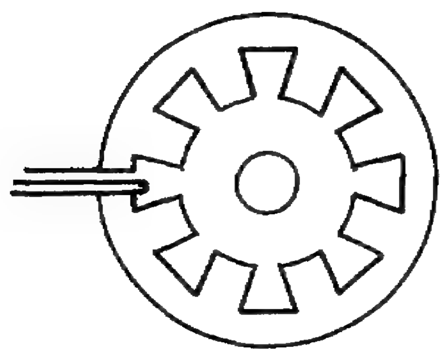
    a. hole and slot resonators.

    b. rising sun resonators.

    c. vane resonators.

    d. slot resonators.

Figure 101. Magnetron Cavity Resonator.



12. A magnetron with slot resonators operating in the pi mode is represented in Figure 102 in the sketch labeled

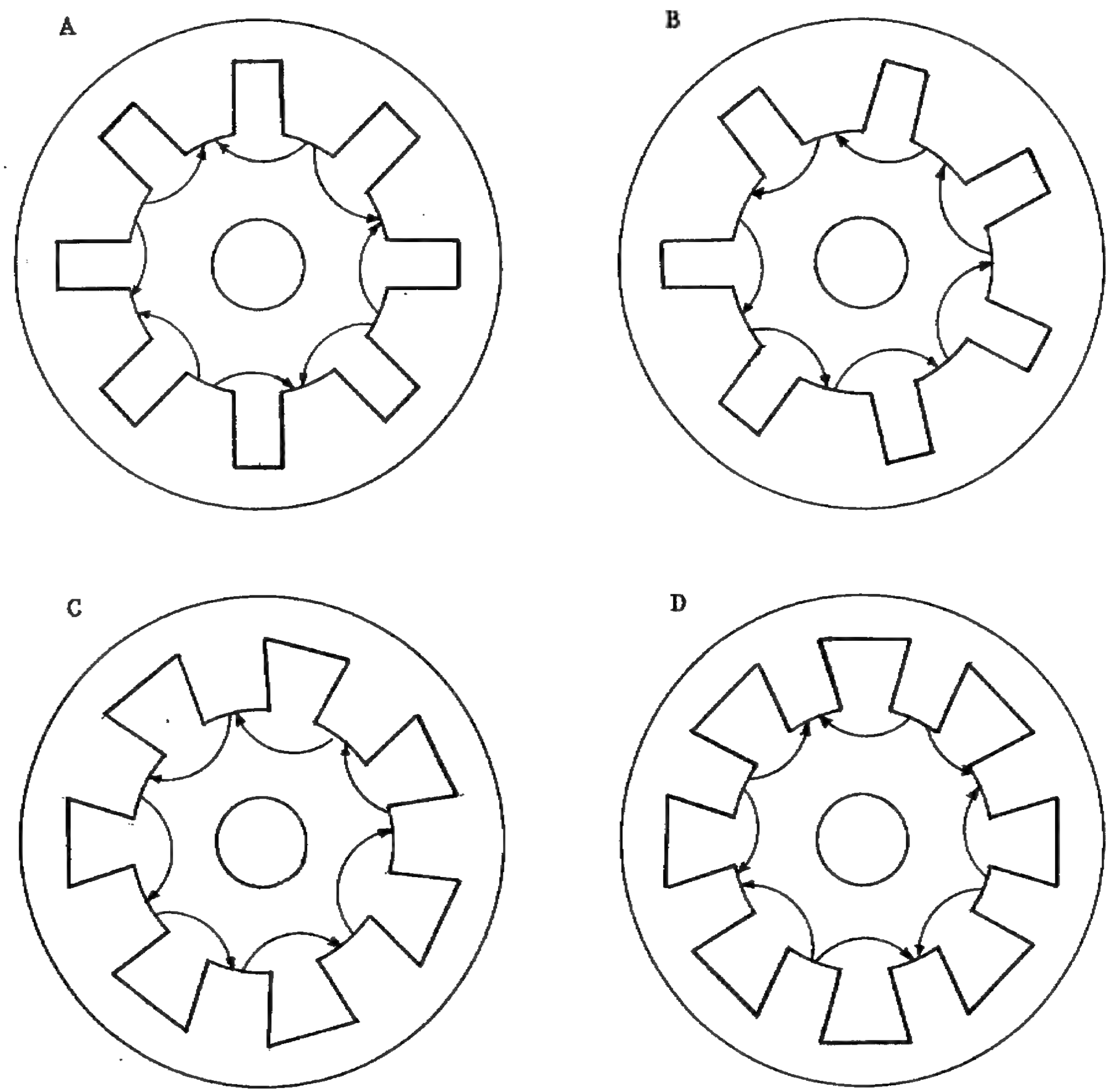
a. A.

b. B.

c. C.

d. D.

Figure 102. Magnetrons.



13. A magnetron differs from a conventional diode tube in that it uses a permanent magnet to deflect the electron beam and its plate is at ground potential. The reason for grounding the plate is to

    a. prevent shock hazards.

    b. reduce magnetron pushing.

    c. permit the use of a conventional filament transformer for the magnetron.

    d. reduce the strength of the electric field required for proper operation.

14. The combination of the electric and magnetic fields causes the electrons to take a twisting spiraling motion toward the anode. The magnetron that has the greatest magnetic field strength is represented in Figure 103 in the sketch labeled

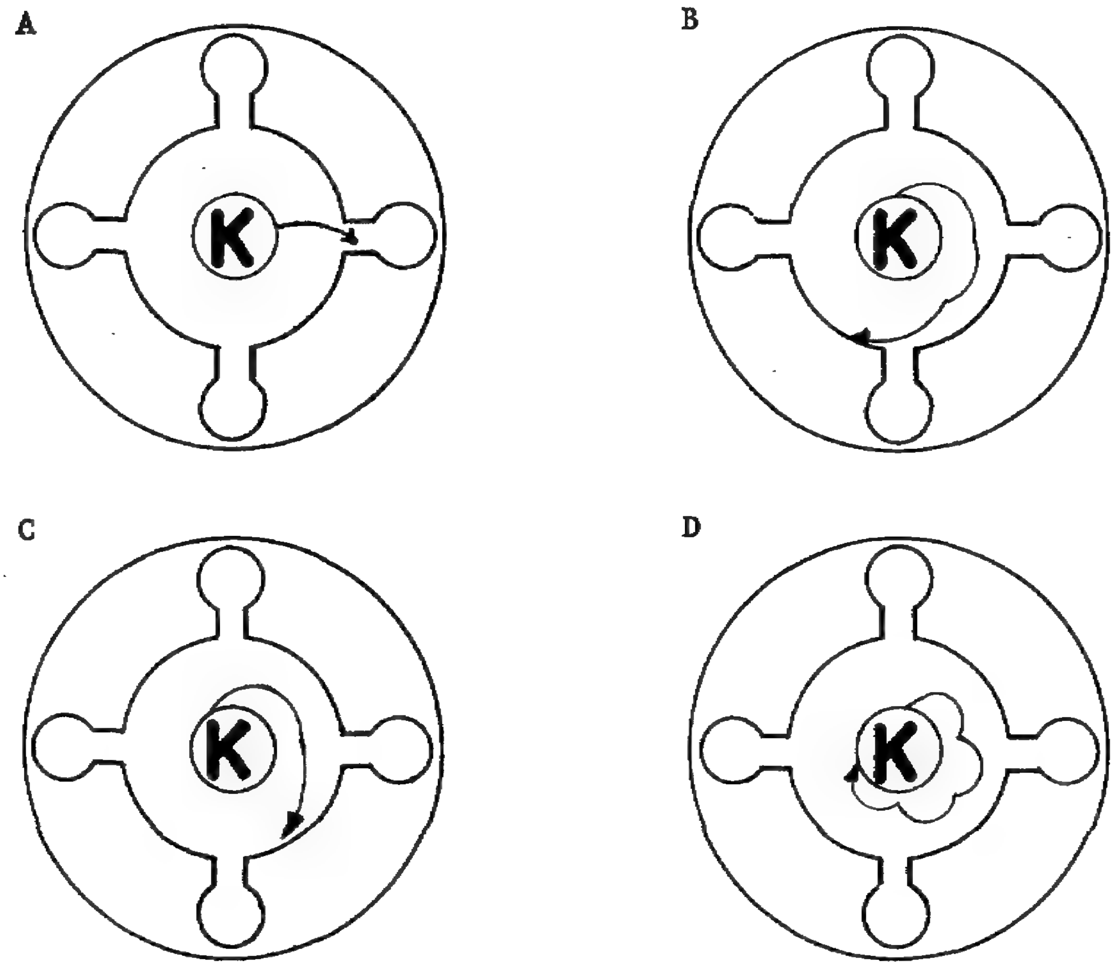
    a. A.

    b. B.

    c. C.

    d. D.

Figure 103. Electron Motion in a Magnetron.



15. What is the purpose in strapping every other segment in a magnetron's anode block?

    a. Maintain a constant electric field between segments.

    b. Ensure that the magnetron oscillates in the pi mode.

    c. Ensure sufficient regeneration.

    d. Prevent magnetron pushing.

16. The straps in a magnetron are designed to be one-half wavelength long and will ensure that the magnetron operates properly. The rising sun type magnetron does not require strapping because

    a. the magnetic field ensures that the RF energy in each slot is 180 degrees out of phase with the energy in the adjoining slot.

    b. it is not pulled off frequency by reflections in the waveguide.

    c. every other vane is larger than the one in between.

    d. it does not operate in the pi mode.

17. The filament starting voltage for a QK324 magnetron is 4.8 volts and the filament running voltage is zero. The reason for using zero volts for the filament running voltage is that the

    a. magnetron's frequency is fixed.

    b. modulator pulse provides filament voltage.

    c. filament is heated by degenerative electrons.

    d. pulse width of the modulator pulse is very narrow.

18. For proper operation in a magnetron, the electrons emitted by the cathode must excite the cavities and also provide regeneration for the cavities. Regeneration is provided by electrons in the magnetron shown in Figure 104, sketch labeled

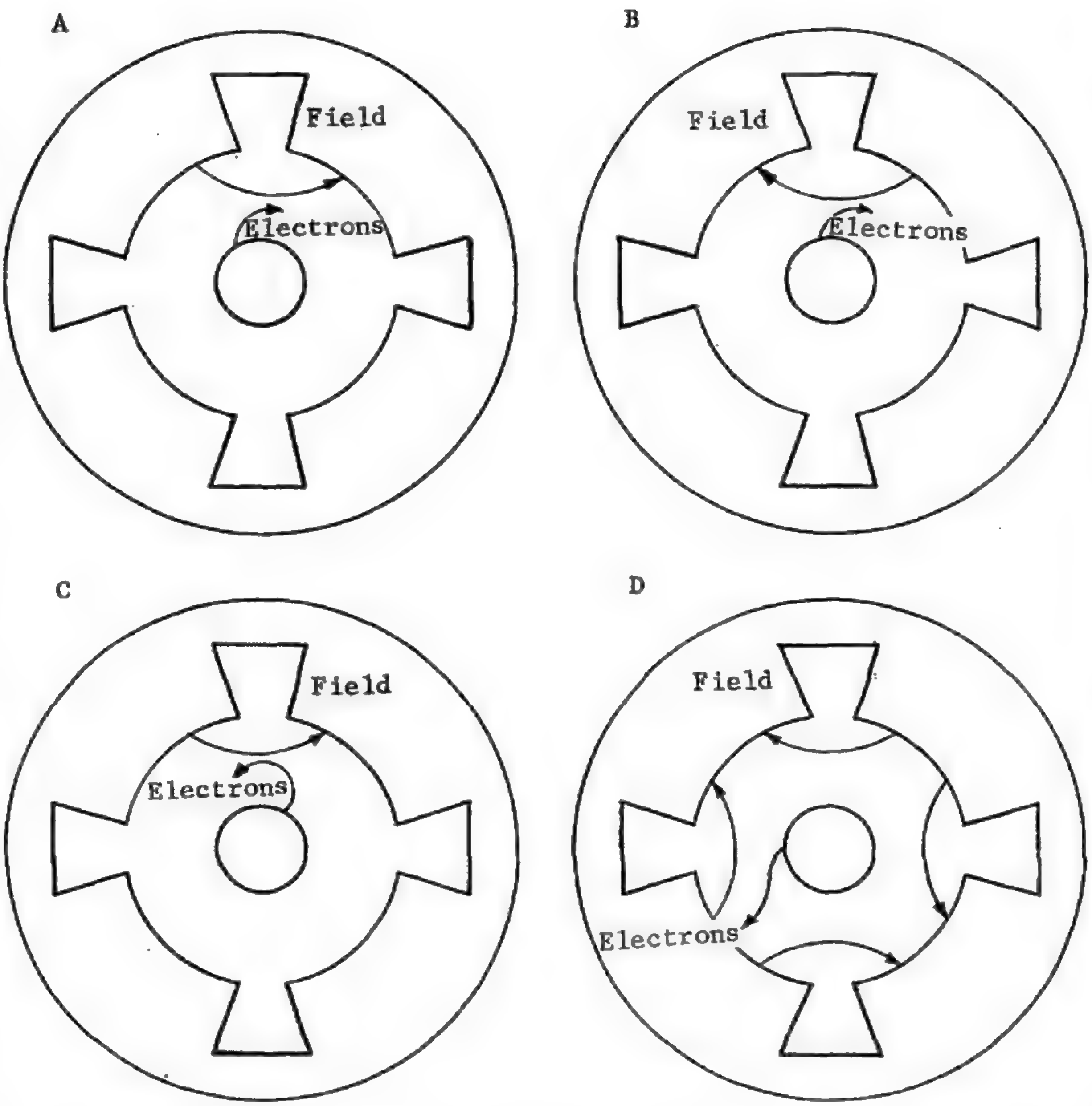
    a. A.

    b. B.

    c. C.

    d. D.

Figure 104. Regenerative Electrons.



19. A great deal of care should be taken when handling a magnetron magnet, so that

    a. the magnetron will not require aging when installed in a radar set.

    b. the magnetron will not be pulled off frequency.

    c. its field strength will not be reduced.

    d. tools will not become magnetized.

20. If the RF output of a magnetron is pulled off frequency, the probable cause of the trouble is

    a. a dented section of waveguide.

    b. a distorted modulator pulse.

    c. an unstable timing trigger.

    d. a weak magnetic field.

Check your answers with lesson 3 Solution Sheet.

LESSON FOUR

ANTENNAS AND WAVEGUIDES

TASK

Describe how RF energy is transferred through waveguides, recognize the various waveguide tuning and coupling devices, identify the various antennas and reflectors used in radar systems, and differentiate between front and rear antenna feed systems.

CONDITIONS

(Performance-Oriented) Given this subcourse, pencil, and paper.

STANDARD

(Performance-Oriented) Demonstrate competency of task skills and knowledge by correctly responding to 75 percent of the multiple-choice test covering radar transmitters.

REFERENCES

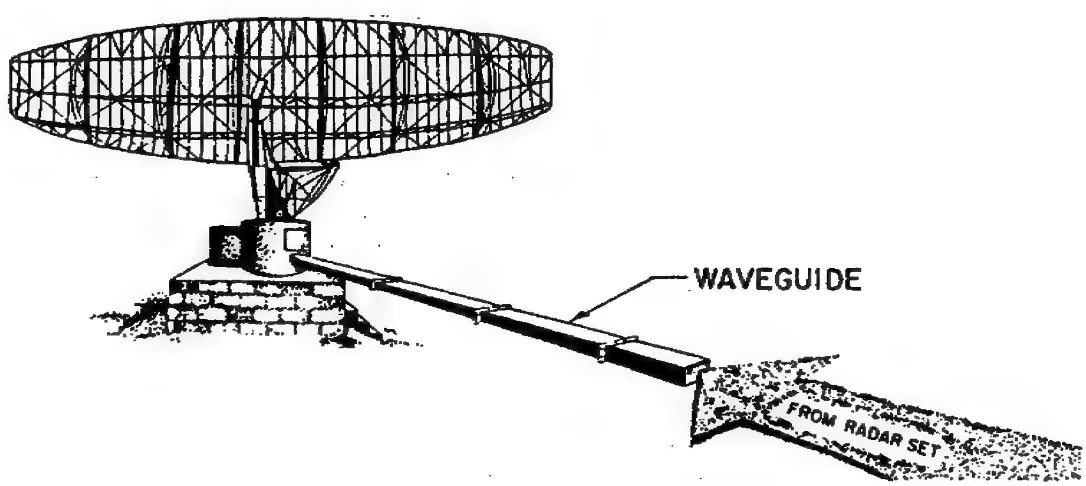
TC 11-67
FM 11-63

Learning Event 1:
WAVEGUIDES

1. General.

All transmission lines have power losses that increase as the applied frequency rises. In fact, at microwave frequencies, ordinary RF transmission lines losses are so great that their use is impractical. As a result, transmission engineers have devised a new transmission medium for guiding microwave energy from one place to another. They use waveguides as the transmission medium. Waveguides give much lower power losses at microwave frequencies than you would get using ordinary RF transmission lines. Figure 105 shows waveguide directing energy to a radar antenna.

Figure 105. Typical Waveguide.



2. Why call it waveguide?

a. You know that we transfer electrical energy in different ways. For example, we use a copper wire to provide a path for DC and low-frequency AC. Similarly, we use an RF transmission line to provide a path for frequencies above 20 kilohertz. Both the copper wire and the transmission line are designed to transfer or guide the electrical energy with a minimum loss of power.

b. When transferring energy from one place to another, power loss goes up as the applied frequency rises. For this reason, DC is easily transferred from one place to another with very little loss. Even low-frequency AC is easily transferred with very little loss of energy. But power losses are especially important at UHF frequencies and above. That's why we use special types of RF transmission lines such as open two-wire line, flexible coaxial line, and rigid coaxial line.

c. Actually, all types of transmission lines, wires, or conductors are used to guide energy. We usually think of this energy in terms of voltage and current. At microwave frequencies, however, the wavelengths are so small that we speak in terms of waves instead of voltage and current. So, at the microwave frequencies, we speak of guiding the wave. Thus, we get the term waveguide.

3. What is waveguide?

a. Waveguide is a hollow, round or rectangular pipe, of specific dimensions. It is the most efficient means we have of transferring or guiding RF energy.

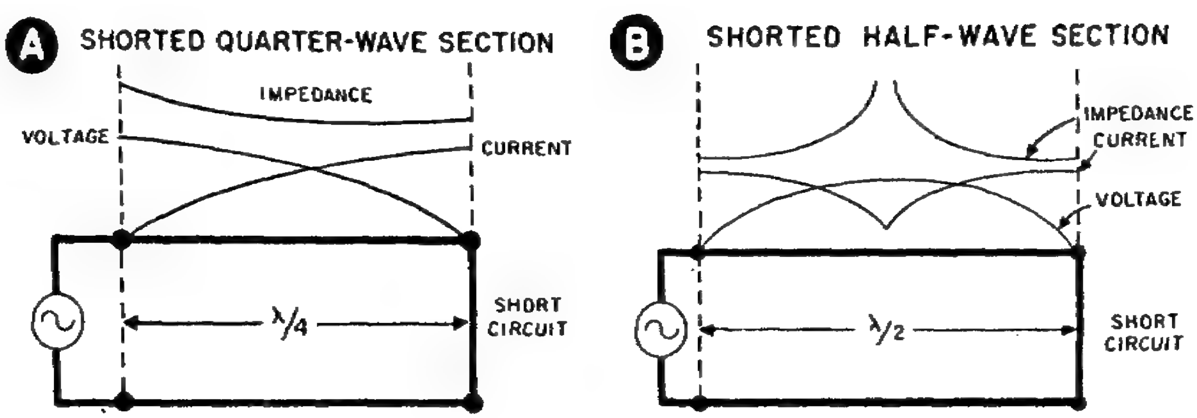
b. In appearance, some waveguides look just like the water pipes in a house. This is why repairmen sometimes call waveguides RF plumbing or just plumbing.

c. In this lesson you will see how waveguide works and learn why it is used at microwave frequencies. You will also see different forms such as straight waveguide, twisted waveguide, and waveguide bends. Before looking at the construction of waveguide, let's review some transmission line characteristics that will help you understand waveguide operation.

4. Characteristics of a shorted quarter-wavelength section.

Figure 106 shows the characteristics of shorted quarter-wavelength and half-wavelength sections of transmission line. The shorted quarter-wavelength section of transmission line shown in Part A of Figure 106 appears as an open circuit at the generator end. The end that appears open has maximum impedance and, when energized, has maximum voltage developed across it.

Figure 106. Characteristics of Short-Circuited Transmission Line Sections.



5. Characteristics of a shorted half-wavelength section.

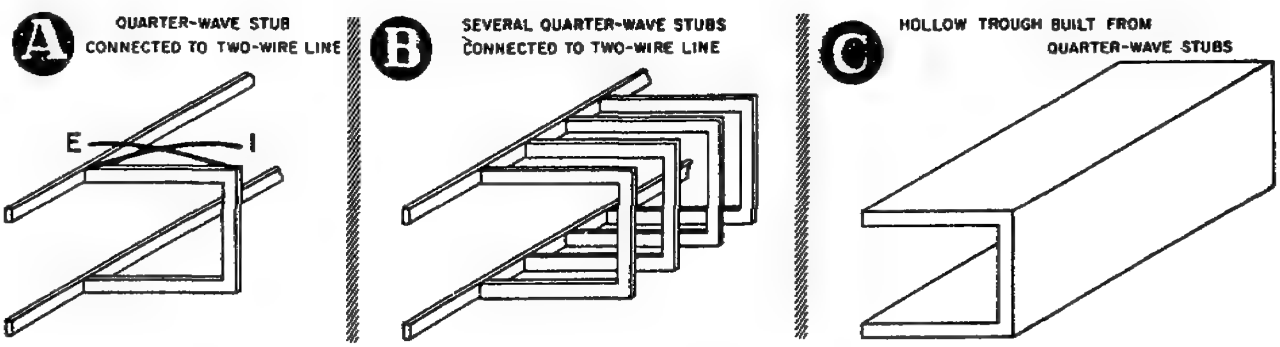
a. The shorted half-wavelength section of transmission line shown in Part B of Figure 106, appears as a short circuit at both ends. It has maximum impedance at the center of the line. When energized, it has maximum voltage developed at the center of the line and maximum current flow at each end.

b. Now let's see how these transmission line characteristics help us construct a hollow metal tube that will guide RF energy.

6. Making a guide for RF energy from two-wire line and quarter-wave stubs.

a. Part A of Figure 107 shows a quarter-wave section (stub) connected to a two-wire transmission line. The voltage and current standing waves of the quarter-wave stub are as shown. Now let's add a few more quarter-wave stubs to the line as in Part B of Figure 107.

Figure 107. Hollow Trough Built From Quarter-Wave Stubs and Two-Wire Transmission Line.

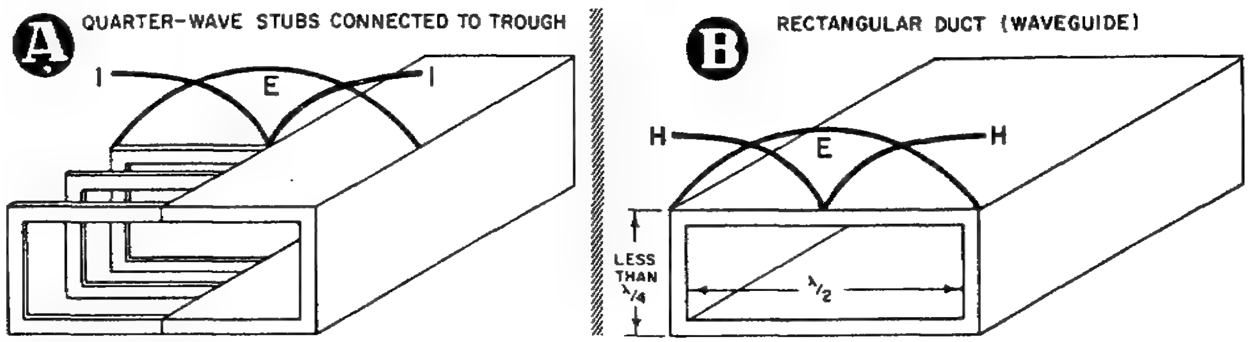


b. The voltage and current standing waves are the same for each stub. If we keep adding quarter-wave stubs to the two-wire line, the electrical characteristics of the line do not change, even though the line changes physically. Finally, you can see in Part C of Figure 107 that if we keep adding stubs to the line, we get a hollow trough with solid walls. We can make this trough as long as we want by merely adding more quarter-wave stubs.

7. Connecting stubs to the other side of the line.

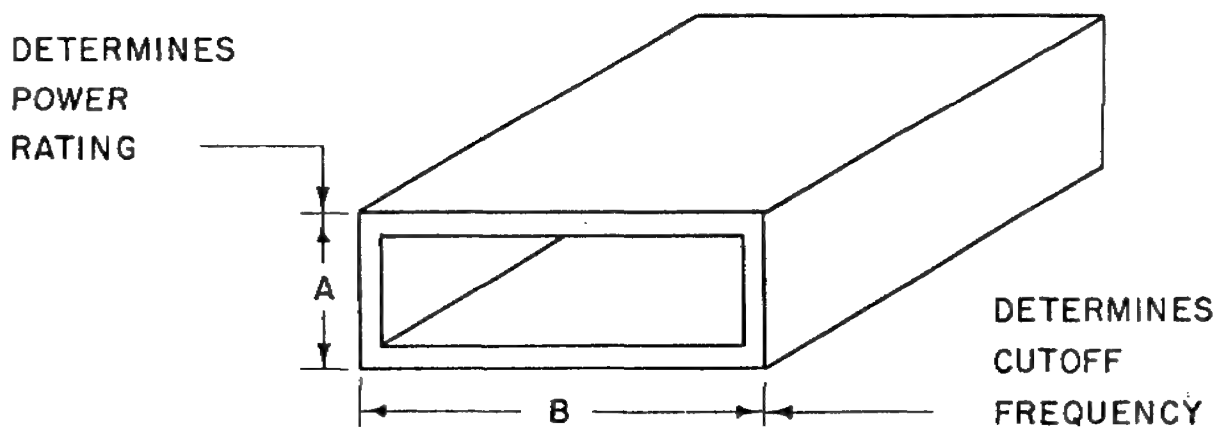
a. Now let's connect some quarter-wave stubs to the other side of the two-wire transmission line. We do this as shown in Part A of Figure 108. You can also see the voltage and current standing waves for the new section. If we continue connecting stubs to this side of the line, we finally get the result shown in Part B of Figure 108.

Figure 108. Rectangular Pipe Constructed From Quarter-Wave Stubs.



b. Notice that what we have constructed is a hollow, rectangular pipe, or duct. Electrically, we have a rectangular duct that is a little over one-half wavelength wide, and a little less than one-quarter wavelength high. We can make the duct as long as we want. This is the most common type of plumbing used to guide RF waves at microwave frequencies. Regardless of the position of the waveguide, the shorter dimension is always called height, and is denoted by the letter A (Figure 109). The longer dimension is called the width, and is denoted by the letter B (Figure 109).

Figure 109. Dimensions of Waveguide Determine Power and Frequency.



c. The height determines the amount of power we can put into the waveguide without arcing. The greater the height, the more power we can inject into the guide.

d. The width determines the lowest frequency we can send down the waveguide. The wavelength of the lowest frequency is twice the width of the guide.

e. Rectangular waveguide sometimes has larger dimensions than those just mentioned. Sometimes, waveguide is round instead of rectangular. We will discuss round waveguide later in the lesson.

8. Energy in the waveguide is contained in the E and H fields.

The RF energy inside the waveguide is contained in the E and H fields just as it is in resonant cavities. You will see in this lesson how these fields are positioned in the waveguide and how they travel from one end to the other.

9. A brief summary.

a. A waveguide is a hollow pipe, usually rectangular, of specific dimensions, used as a transmission medium for guiding microwaves.

b. Waveguide is commonly called plumbing.

c. Waveguide is usually a little over one-half wavelength wide, less than one-quarter wavelength high, and long as required.

d. Waveguide is an efficient transmission medium because it has very little loss due to skin effect, dielectric, and radiation.

e. We said that the RF energy inside waveguide is contained in the E and H fields just as it is in resonant cavities. Now let's look at the way these fields are contained in waveguides.

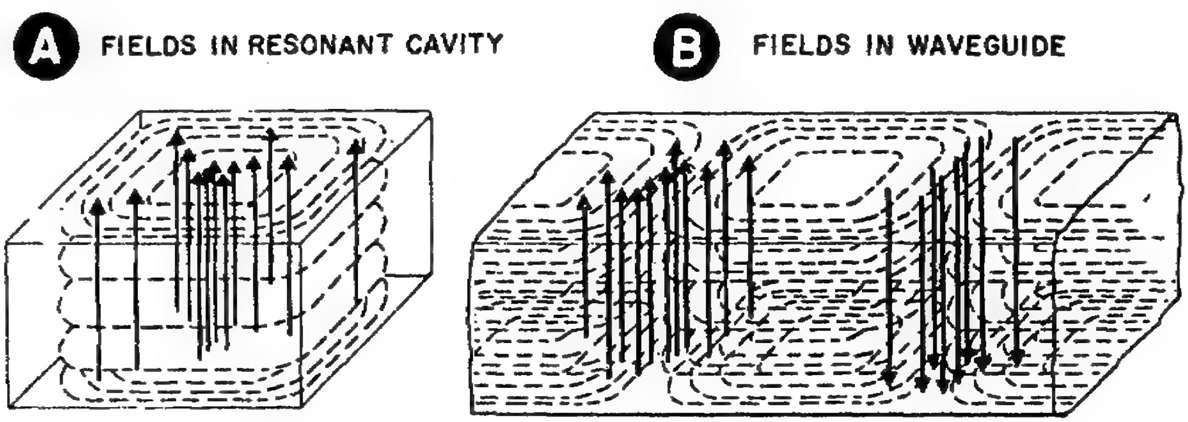
10. Positioning of E and H fields in waveguide.

a. You know from resonant cavities, that we can confine electric and magnetic fields in a hollow chamber. We did this with the electrical energy applied to a resonant cavity. You also found out that a resonant cavity is constructed in such a way that the fields within the cavity are completely

reflected from one wall. The reflected energy returns to the point where it was applied and is completely reflected again. These reflections continue for a period of time; so we say the cavity is oscillating.

b. Now, if we terminate a resonant cavity in its characteristic impedance, the energy applied will be absorbed by the load, and there won't be any reflections or oscillations. This is exactly what we do with waveguide. The fields in a waveguide, however, are not in the same positions as they are in a resonant cavity. Look at Figure 110.

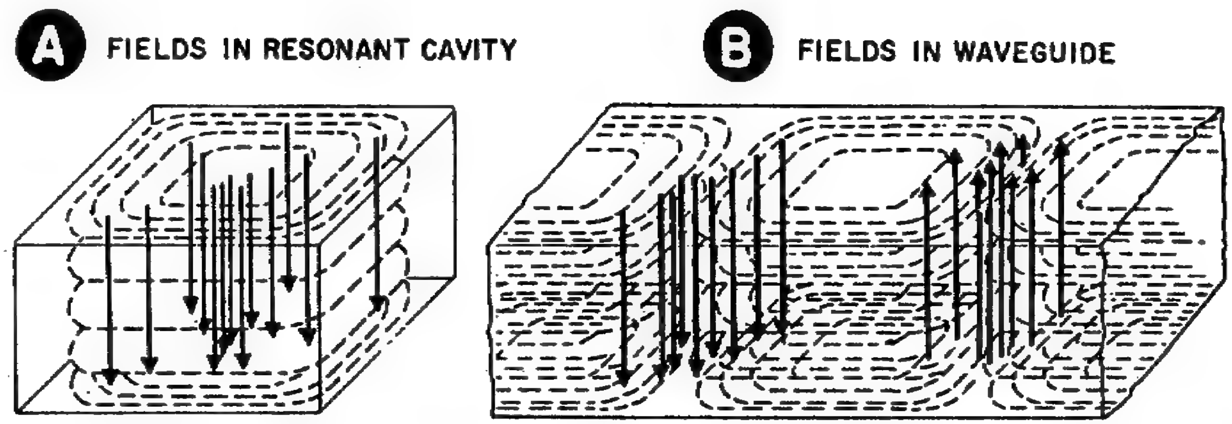
Figure 110. The E and H Fields Inside a Resonant Cavity and a Waveguide.



c. Part A of Figure 110 shows a resonant cavity with its E and H fields. Part B of Figure 110 shows a length of waveguide with its E and H fields. Notice that the fields in the waveguide are in-phase, but those in a resonant cavity are 90 degrees out-of-phase with each other.

d. Both illustrations in Figure 110 show the fields at one instant of time. Figure 111 shows the field one-half cycle later.

Figure 111. The E and H Fields One-Half Cycle Later.



e. In Figure 111, the fields have changed from a maximum positive direction to maximum negative direction. However, the variation is sinusoidal. That is, they change just as a sine wave of voltage or current changes from maximum positive to maximum negative. The big differences between the fields contained in a resonant cavity and the fields in waveguide are as follows:

(1) The fields in a resonant cavity are completely reflected and oscillate until all their energy is dissipated. Also, the fields in a resonant cavity are 90 degrees out-of-phase.

(2) The fields in a waveguide differ in that they travel down to the end of the guide and are absorbed because the guide terminated in its characteristic impedance. Also, they are in-phase with each other.

11. Summing up waveguide field characteristics.

a. The points or areas of maximum electric (E) field in a waveguide are in the center of the hollow chamber.

(1) These areas of maximum E field occur every half wavelength along the length of the guide.

(2) The areas of maximum E field are the same areas that have maximum impedance.

b. The points or areas of maximum magnetic (H) field in a waveguide are along the walls of the chamber. The areas of maximum H field are the same areas that have minimum impedance.

c. All of the fields are within the waveguide.

d. The only current flow in waveguide is on the inside surface of the walls just as it is with resonant cavities. This is one reason why waveguide is so efficient.

e. We stated earlier that transmission lines have losses, due to skin effect, dielectric, and radiation. These losses are very slight with waveguide. Let's find out why.

12. Why waveguide has very low loss due to skin effect.

a. When we transmit RF energy along a wire, the current flows on the outer edge of the wire. As we increase the applied frequency, the current flows more and more on just the outer edge (or circumference) of the wire. We call this action skin effect. This means that, although the wire may be two inches in diameter, only one small section of the wire is actually carrying current.

b. The action of skin effect is the same as if we reduced the diameter of the wire or added resistance to it. This results in heat being generated, and the electric power dissipated in the form of heat is loss. This is the reason, then, that wire has high losses due to skin effect at higher RF frequencies.

c. In waveguide, current flows only along the inside surface of the guide, but remember that waveguides have four solid walls to carry the current. Therefore, the current-carrying area is much greater in waveguide than in wire. This greater area has very little resistance, so losses due to skin effect are very low.

d. The inside walls of waveguide are sometimes silverplated or gold-plated as they are in resonant cavities. Plating the walls reduces any resistance the walls have and further decreases losses due to skin effect.

13. Why waveguide has very low dielectric loss.

a. You know that any two-wire or coaxial type transmission line has some kind of insulation to keep the two wires apart. Any insulating material, such as rubber, plastic, or even air is actually a dielectric between the two conductors. So, there's always some slight current flow through the dielectric. We call this slight current flow between the two conductors leakage current, and the resulting loss of energy is called dielectric loss.

b. The dielectric loss of air is so small that we can ignore it. Air is the only dielectric contained in waveguide; therefore, waveguide has negligible dielectric loss.

c. The third kind of loss most RF transmission lines have is radiation loss.

14. Why waveguide does not have radiation loss.

a. You know that current flow in a conductor sets up a magnetic field at tight angles around the conductor. The magnetic field produces an electric field, and both these fields are radiated into space. This radiation is a loss of energy except in applications where we want to radiate energy out into space, such as with an antenna.

b. You see then, that all unshielded transmission lines radiate some energy. We call this loss of energy radiation loss.

c. Energy traveling through waveguide is contained within the walls of the waveguide. All current flow is on the inside surface of the walls, and no energy can go out into space. Hence, waveguides have no radiation loss.

d. You have just learned how transmission line losses compare with the slight losses of waveguide. Table III shows this comparison and also shows the frequency bands for waveguide and the other various types of transmission lines.

Figure 112. Comparing Waveguide and Transmission Lines.

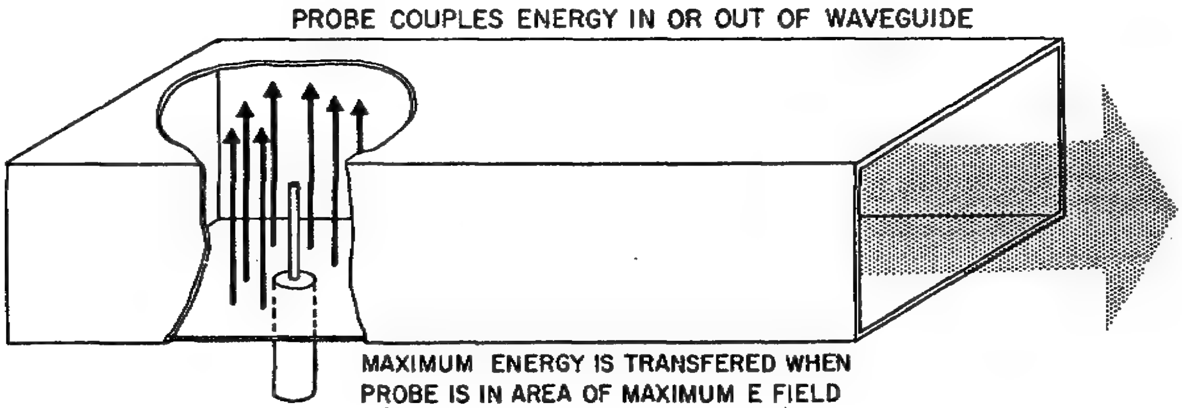
TYPE	FREQUENCY BAND	LOSSES DUE TO SKIN EFFECT	LOSSES DUE TO DIELECTRIC	LOSSES DUE TO RADIATION
Waveguide	S, X, and K bands; used exclusively at X and K bands.	Very low.	So low, can be ignored.	None
Rigid coaxial line	S band.	Higher than waveguide losses.	Very low.	None
Flexible coaxial line	Below S band; small sections are used for S and X band.	Higher than rigid coaxi-al losses.	Higher than rigid coaxial losses.	None
Open two-wire line	VHF and below.	Higher than flexi-ble coaxial line losses.	Very low.	High
Insulated two-wire line	VHF and below.	Higher than flexible coaxial line losses.	Higher than rigid coaxial line losses.	High

e. Now that you have learned how energy travels along waveguide and why waveguide is very efficient, let's see how you couple energy into or out of waveguide.

15. Energy is usually coupled into waveguide with a probe.

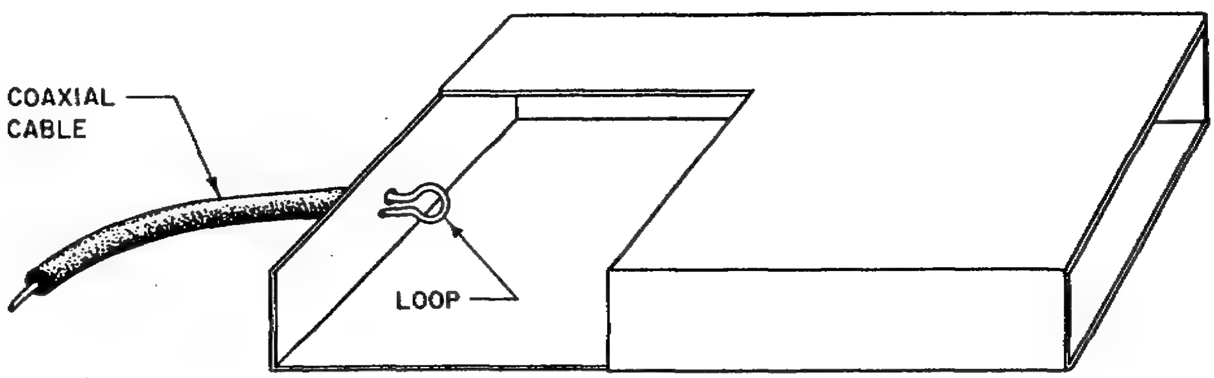
a. The most common method of coupling energy into waveguide is with a probe (Figure 113). This method is identical to probe coupling into a resonant cavity. That is, the probe is placed in the waveguide at the center of the width (B dimension) and a quarter-wavelength from the end. This point gives maximum E field in the center of the guide and maximum H field along the walls of the guide.

Figure 113. Probe Coupling into a Waveguide.



b. Although probe coupling is used most often, we sometimes use loop-coupling or slot-coupling just as with resonant cavities. Figure 114 shows an example of loop coupling into a waveguide.

Figure 114. Loop Coupling into a Waveguide.



c. Now let's see how energy is coupled out of waveguide. The method used depends upon the device to which the waveguide is coupled.

16. Waveguides are coupled to one of three devices.

a. The three principal uses of waveguide are as follows:

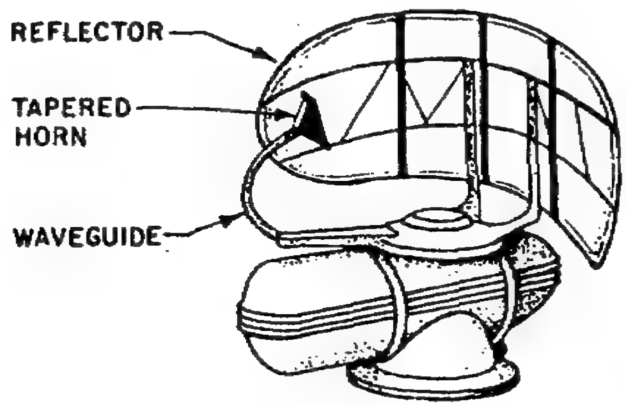
(1) Guiding energy to an antenna.

(2) Guiding energy to test equipment.

(3) Guiding energy to a dummy load.

b. Waveguide is used extensively to guide RF energy to an antenna. Figure 115 shows a waveguide feeding a reflector. A reflector is an important part of many antennas because it is used to direct the RF energy into space. Figure 115 shows how energy is coupled from the waveguide, through the air, to the reflector using a "horn."

Figure 115. Waveguide Coupled to a Reflector.



17. Horn coupling.

a. Notice in the figure that the waveguide is flared at the end and resembles a horn. A horn is a common method of coupling energy from a waveguide to a reflector.

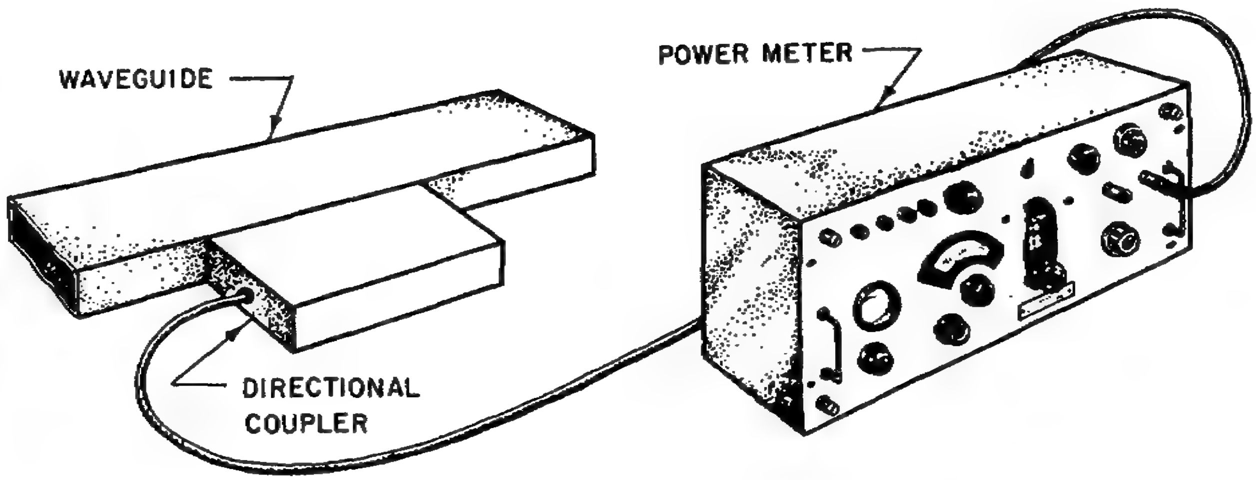
b. You might think it would be easier if we just had the waveguide opening pointed at the reflector. Well, it would be, so why bother with a horn? Here's the reason: Remember, we said a waveguide should be terminated in its characteristic impedance. That's the purpose of the horn; it's an impedance-matching device. As the sides of the waveguide get wider, its impedance increases.

c. A horn then, matches the comparatively low impedance of the waveguide to the higher impedance of the air.

18. Coupling waveguide to test equipment.

As a repairman, it is your job to test radar equipment. Many times you will have to make tests in the RF section of the equipment. This means you will have to connect test equipment to waveguide. You do this with a device called a directional coupler. A directional coupler takes a sample of the energy from the waveguide and couples it to the test equipment. An example of directional coupling from waveguide to a power meter is shown in Figure 116.

Figure 116. Waveguide Connected to Meter
Through a Directional Coupler.

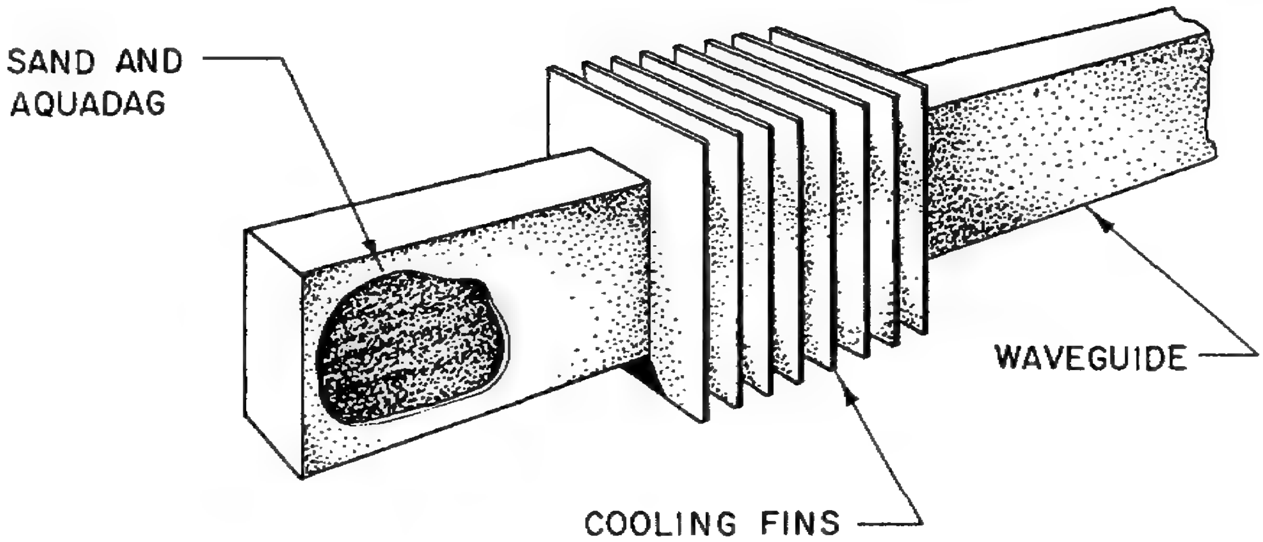


19. Next, coupling waveguide to a dummy load.

a. Sometimes you will have to work on equipment that is operating, but not radiating energy. This happens many times when military security forbids any transmission of power. When you want your equipment to be in full operation, but not radiating any power, you use a dummy load. A dummy load is a device which absorbs RF energy instead of radiating it.

b. Dummy loads used for communications equipment are usually resistors, light bulbs, or power meters. Radar sets use resistive dummy loads like the one shown in Figure 117. The dummy load shown is a section of waveguide filled with mixture of sand and aquadag. All the energy traveling down the waveguide is dissipated in the form of heat by the sand and aquadag, thus no energy is radiated. The outside of the waveguide has cooling fins which help dissipate the heat.

Figure 117. Waveguide Terminated With a Dummy Load.



20. Reviewing methods of coupling energy from a waveguide.

a. The main purpose of waveguide is to couple RF energy to an antenna, a dummy load, or test equipment.

b. Waveguide is usually coupled to a reflector through an impedance-matching device called a horn.

c. Waveguide is usually coupled to test equipment through a directional coupler which takes a sample of the energy in the waveguide.

d. A dummy load absorbs RF energy and is connected to waveguide to prevent radiation.

e. The energy fed to a dummy load is dissipated in the form of heat.

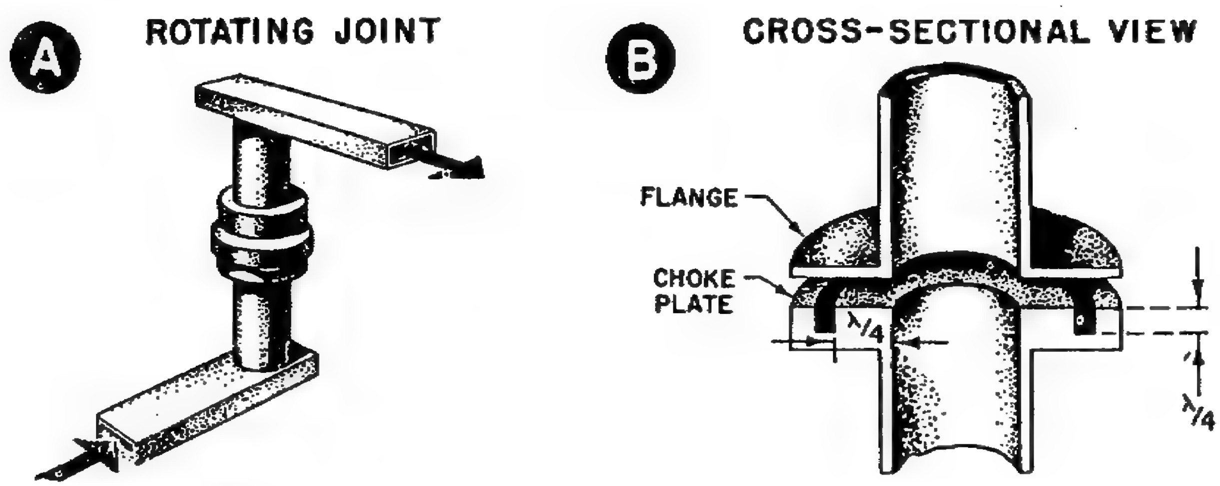
f. So far we have spoken only about rectangular waveguide, but in some applications round waveguide is used. One such case is when we want one end of the waveguide to rotate while the other end remains stationary. The best example of this is when waveguide is used to guide energy from a transmitter to a rotating antenna. The waveguide section connected to the transmitter must remain stationary, but the waveguide section connected to the antenna or reflector must be able to rotate. We do this by using a section of round waveguide called a rotating choke joint.

21. Round waveguide used as rotating choke joint.

a. Part A of Figure 118 shows a connection that lets us rotate one section waveguide while the other section remains stationary. This round section waveguide, called a rotating choke joint, is a poor mechanical connection but a good electrical connection. The cross-sectional view in Part B of Figure 118 shows you why.

b. You see in Part B of Figure 118 that there is no direct mechanical connection between the two sections of waveguide. Instead, there is a small gap between the flange side and the choke plate side, and energy within the waveguide tries to leak through the gap. Note the dimensions of the choke joint and you will see why it doesn't.

Figure 118. Rotating Choke Joint.



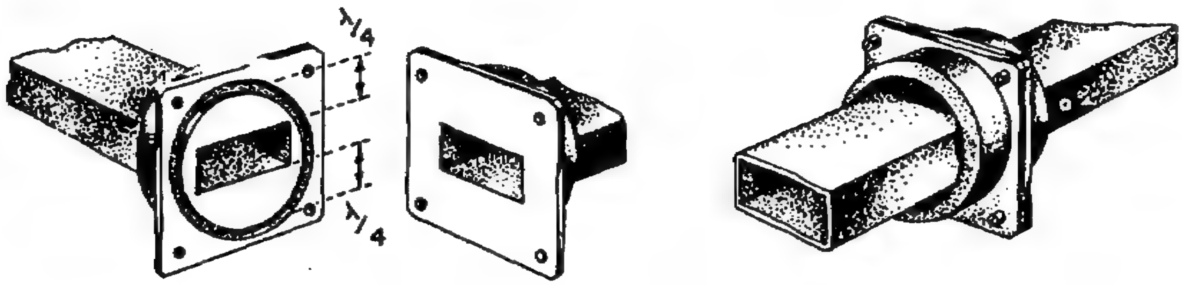
c. First, the length from the bottom of the choke groove (which is shorted) to the top of the groove is one-quarter wavelength. Then, the length from the top of the groove to the inside of the waveguide wall is also one-quarter wavelength. In other words, the length from the bottom of the choke groove to the inside wall of the waveguide is one-half wavelength. Thus, the short at the bottom of the slot is reflected back to the inside wall of the waveguide as a short.

d. The inside wall, then, appears as an area of minimum impedance which is an electrical short. Therefore, although there is no direct physical connection between the two sections of waveguide, there is an electrical short circuit. Any energy traveling down the waveguide passes from one section to the other with a minimum loss of power.

22. Fixed rectangular joints.

a. Waveguide systems usually have several sections that can be taken apart for inspection, cleaning, and easy replacement. Systems with several sections also allow for heat expansion. To minimize reflections, two sections are usually coupled with a joint similar to the rotating choke joint. Figure 119 shows a typical connection.

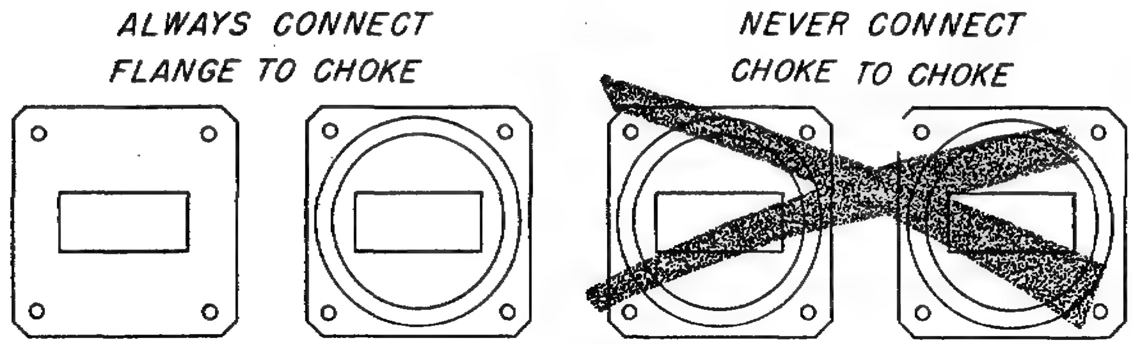
Figure 119. Rectangular Waveguide Joint.



b. As with rotating joints, one section is fitted with a choke plate and the other section with a flange. The operation of this fixed choke joint is exactly the same as that of the rotating joint. There is one difference, however, between circular and rectangular waveguide joints. In circular waveguide, the choke groove is a quarter wavelength between all points of the inner wall of the guide. With rectangular waveguide, the groove is a quarter wavelength away from the inner walls at only two points as shown in Figure 119. These two points, however, are located where the electric field is maximum, so there is only a slight loss of energy at the other points.

c. When you connect two sections of waveguide, it is important that you put the correct ends together. Otherwise, serious reflections will occur, causing a loss of power. The right and wrong ways of connecting sections are shown in Figure 120.

Figure 120. Correct and Incorrect Joint Connections.

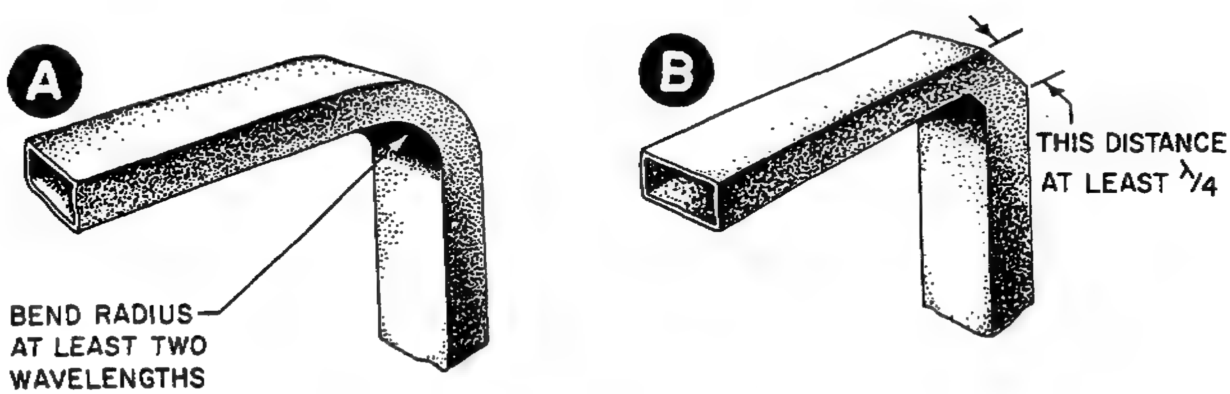


d. Rotating and fixed choke joints are just two variations of basic waveguide. Some other variations are bends, twists, and flexible waveguide. Let's see what these types of waveguide look like, and learn why we use them.

23. Waveguide bends guide RF energy around corners.

a. Sometimes, to extend waveguide from one place to another, such as around a corner, a waveguide section is formed into a special shape called a bend. Two kinds of waveguide bends are illustrated in Figure 121.

Figure 121. Waveguide Bends.



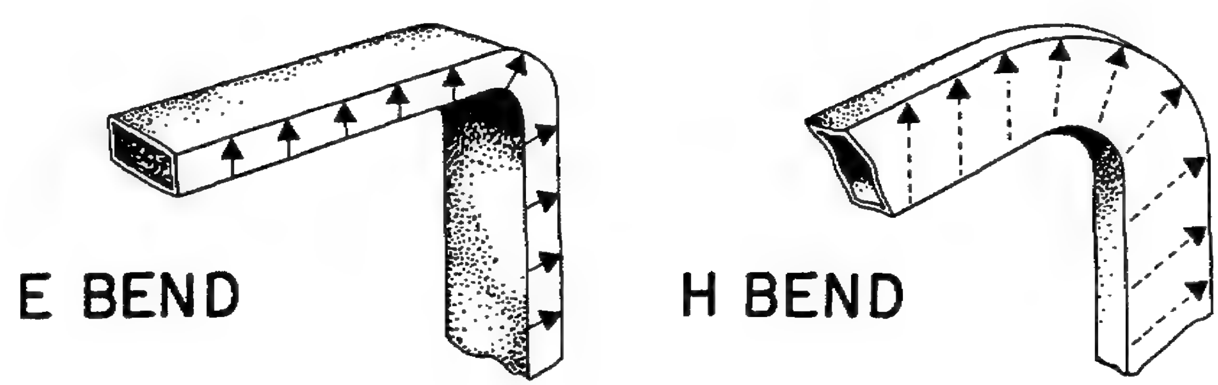
b. The bend in Part A of 116 is called a smooth bend, and the one in Part B is a mitered bend. The bends are special because they have specified lengths. Notice that the smooth bend radius must be at least two wavelengths for a 90

degree turn. The mitered bend must be at least one-quarter wavelength long between the two points indicated. Both bends result in a 90 degree turn, but they are gradual (not sharp) turns. We make the bends gradual to prevent reflections that cause power loss. Bends in rectangular waveguide are further classified as E or H bends.

24. What are E and H bends?

Figure 122 shows both E and H waveguide bends. An E bend is one in which the waveguide is bent in the plane of the electric field. An H bend is one in which the waveguide is bent in the plane of the magnetic field. Figure 122 shows how the E and H fields change from a horizontal to a vertical plane in their respective bends.

Figure 122. E and H Bends.



25. Twisted waveguide is used to change the plane of polarization.

a. We describe the position of an electromagnetic field with respect to the earth, using the term polarization. If the E field is vertical with respect to the earth, we say the electromagnetic field is polarized horizontally.

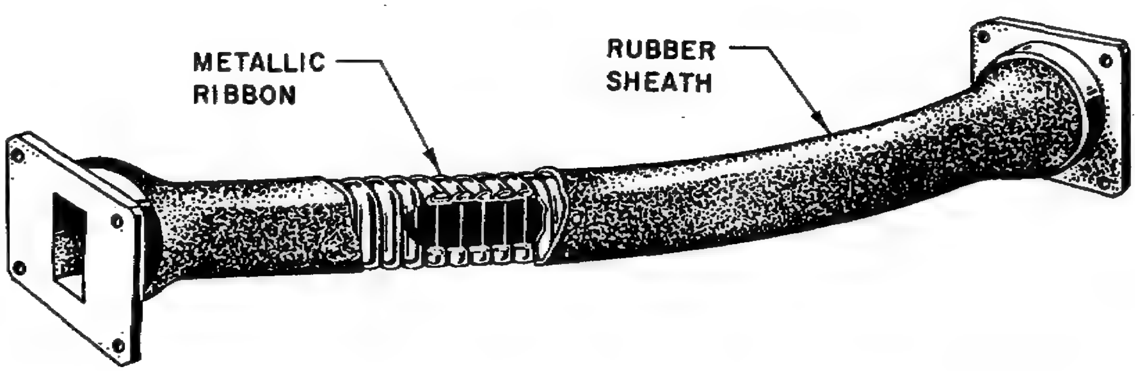
b. Sometimes, to simplify mechanical layout, the field in a waveguide is polarized in a different plane than the one desired at the output. To get the proper polarization at the output of the waveguide, a twisted section is used. A twisted section of waveguide must be at least two wavelengths long to prevent reflections and loss of power. Figure 123 shows how a vertically polarized wave is changed to a horizontally polarized wave by a twisted section of waveguide.

Figure 123. Twisted Section of Waveguide.

26. Next, flexible waveguide.

a. Flexible waveguide, like the section shown in Figure 124, is used when a special type of bend is needed, or because of its adaptability to any bend. This type of flexible waveguide consists of many loops of flat metal ribbon. Each loop has electrical contact with the loop next to it. A rubber sheath surrounds the loops and holds them in place. Notice that the inside of the flexible section presents some surfaces at right angles to the field traveling down the guide. These slight obstructions cause the field to be reflected and there is some loss of energy. For this reason, flexible waveguide sections are not used very often, except in cases where this loss of energy causes no problems. One such case is where we take just a sample of the energy and feed it to test equipment.

Figure 124. Flexible Waveguide.



b. That completes the coverage on the various forms of waveguide. Figure 125 summarizes the information on these waveguide components.

Figure 125. Comparing Waveguide Components.

NAME	PURPOSE
CHOKE JOINT	Connects two waveguide sections without loss of energy.
ROTATING CHOKE JOINT	Connects fixed waveguide to rotating waveguide without loss of energy.
E AND H BENDS	Guides waves around corners without introducing reflections.
TWIST	Changes polarization of field within the waveguide.
FLEXIBLE WAVECUIDE	Special bends.

c. You have learned that we use waveguide sections of various shapes to change the direction or polarization of the fields. Now you will learn how to tune waveguides, and how to adjust the power within the waveguide.

27. Methods of tuning waveguide.

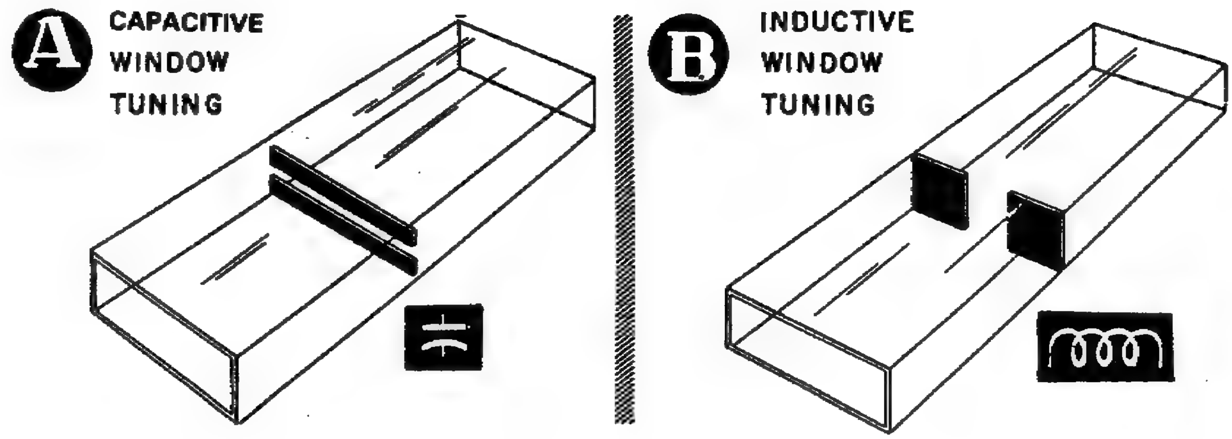
a. Waveguide must be tuned just as resonant cavities or transmission lines must be tuned. Tuning waveguide means that you change its impedance to match the impedance of the device to which it is connected. This may be an antenna, a magnetron, or any other RF component.

b. Waveguide tuning methods are similar to those used in tuning resonant cavities. That is, you change the capacitive reactance so that it cancels the inductive reactance of the waveguide. Or, you change the inductive reactance so that it cancels the capacitive reactance of the waveguide. The first type of tuning we will consider is that done at the factory where the waveguide is constructed.

28. Fixed window tuner.

a. Figure 126 shows two metallic fins or plates placed in a waveguide in such a way that they reduce the cross-section of the guide. The metal partitions are reactive elements called irises. The space between the metal plates is called a window; that's why we call it window tuning. The irises change the impedance characteristics of the waveguide by obstructing the electric and magnetic fields in the guide.

Figure 126. Capacitive and Inductive Window Tuning.



b. Part A of Figure 126 shows two metal partitions placed in a section of waveguide so they obstruct the electric field. This type of tuning is called capacitive window tuning. Here is how capacitive window tuning works. Suppose there is an undesirable inductive reactance at a particular point in a section of waveguide. You know that inductive and capacitive reactances are 180 degrees out of phase with each other. So, to get rid of the inductive reactance, all you have to do is add an equal capacitive reactance that cancels the inductive reactance. That is what happens when we place metal partitions across the width of the waveguide. The irises obstruct the passage of the electric field and act as a capacitive reactance. The further we extend the irises into the waveguide, the more capacitive reactance we add at that point.

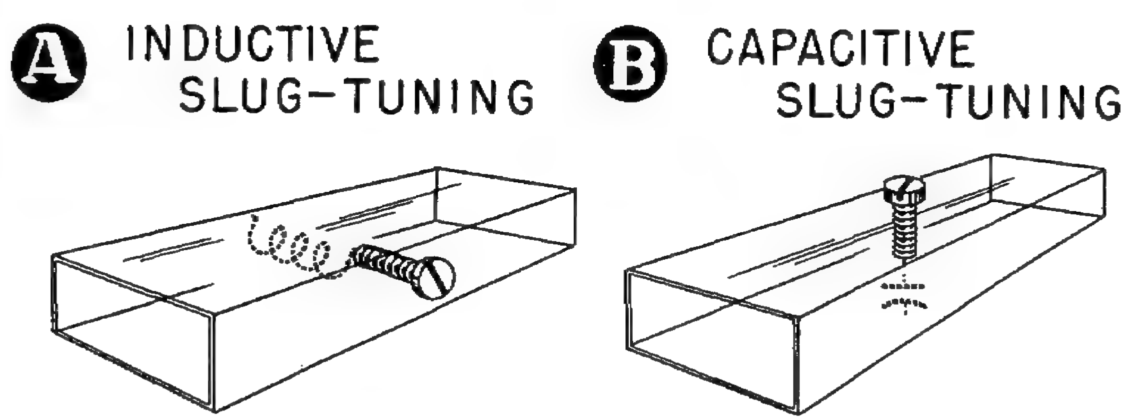
c. Another kind of window tuning called inductive window tuning is shown in Part B of Figure 126. This time, the metal partitions, or irises, are placed near the side walls of the waveguide. These irises obstruct the magnetic field, and act as an inductive reactance. The further we extend the irises into waveguide, the more inductive reactance we get. We place metal partitions near the side walls of the waveguide to cancel any undesirable capacitive reactance.

d. Both types of window tuning are usually done at the factory, and it won't be necessary for you to adjust them. However, we do have waveguide that you, as a repairman, will have to tune. Most adjustable waveguide tuning is done with a slug.

29. Slug tuning.

You tune waveguide with a slug the same way that you tune a resonant cavity with a slug. If the slug is inserted in the side wall of the waveguide as in Part A of Figure 127, it affects the magnetic field and tunes the waveguide inductively. If the slug is inserted in the top of the waveguide, as in Part B of Figure 127, it affects the electric field and tunes the waveguide capacitively. Besides adjusting waveguide to change its impedance, you sometimes adjust the power level inside a waveguide by using an attenuator.

Figure 127. Waveguide Tuned With a Slug.

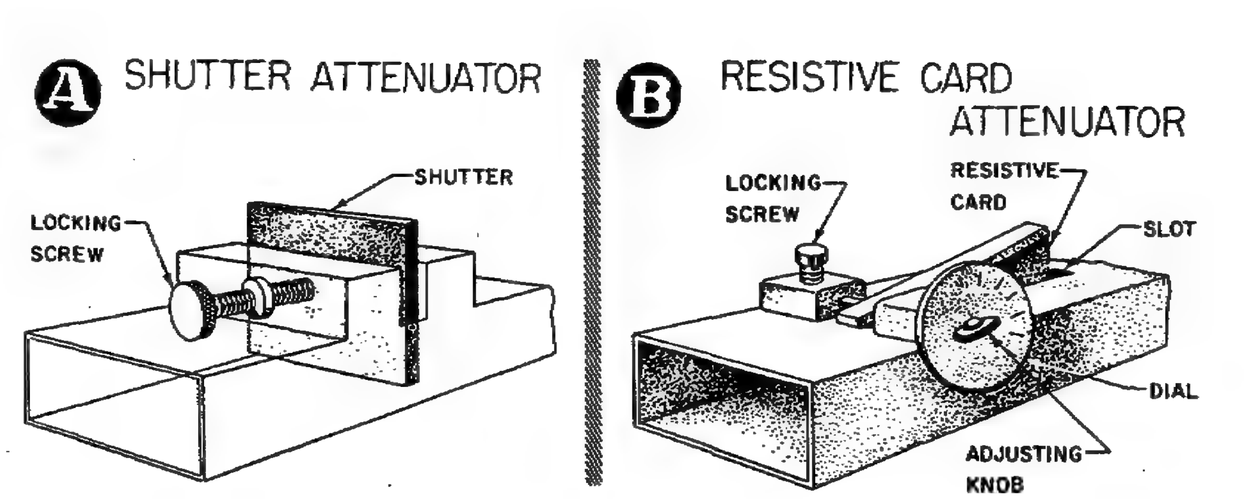


30. Waveguide attenuators.

a. As you recall, an attenuator is a device used to reduce electrical energy. The two main types of attenuators used with waveguide are the shutter and resistive card.

b. Part A of Figure 128 shows a shutter attenuator with its locking screw. As you lower the shutter into the waveguide, it reflects some of the energy traveling down the guide. The reflected energy is a loss, and the power on the other side of the shutter is less than that on the input side. We can say then, that the shutter attenuates (reduces) the power. The more you lower the shutter into the waveguide, the more attenuation you get. The locking screw holds the shutter at the desired position. Notice that a shutter attenuator looks like the iris used in waveguide tuning. Actually, any tuning device results in some loss of power and can be used as an attenuator. The methods we use specifically for attenuation, however, are more convenient for this purpose.

Figure 128. Waveguide Attenuators.



31. Next, dissipative attenuator (resistive card).

a. You use a resistive card such as the one shown in Part B of Figure 128 as a variable attenuator. The card is inserted into the waveguide parallel to the electric field and does not introduce reflections. Instead, the card is coated with a resistive material that absorbs (or dissipates) energy. The further you insert the card into the waveguide, the more attenuation you get.

b. Figure 129 summarizes the information on the last four RF components covered.

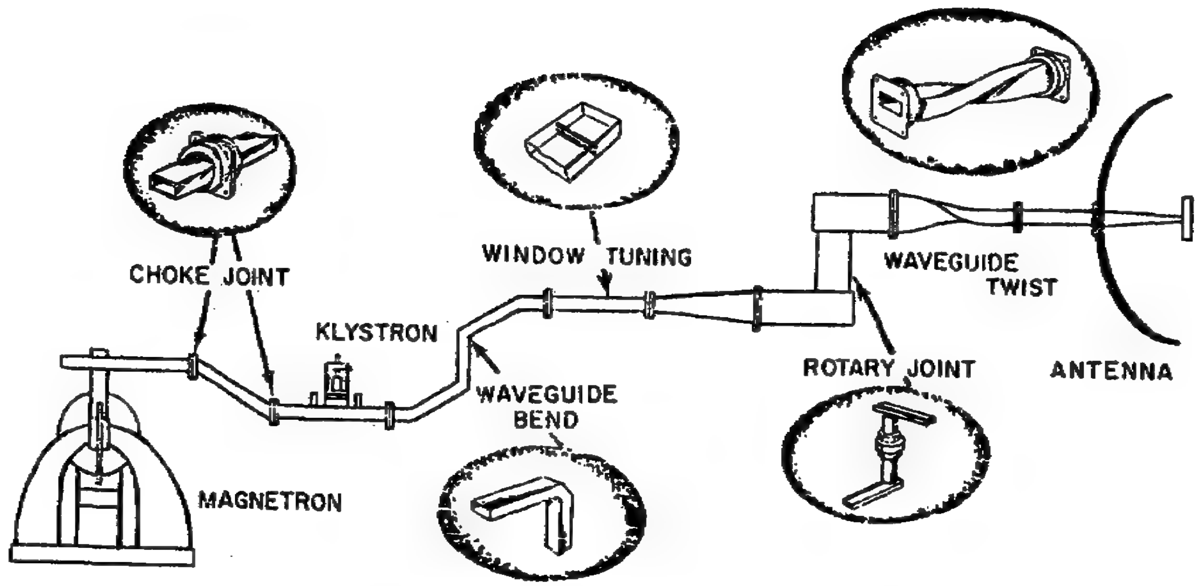
Figure 129. Review of RF Components.

NAME	PURPOSE
WINDOW TUNER	Fixed impedance-matching method done at factory.
SLUG TUNER	Adjustable impedance-matching method done in the field.
SHUTTER ATTENUATOR	Attenuates field within waveguide by introducing reflections.
RESISTIVE-CARD ATTENUATOR	Attenuates field within waveguide by absorbing energy.

32. Complete system of RF components.

A complete RF system of a typical radar set is shown in Figure 130. This figure shows you how waveguide and other RF components guide energy from the magnetron to the radar antenna. Note carefully the pictorial view of the important RF components and their location in the system.

Figure 130. Radar RF System.



33. Handling waveguide.

a. You have learned in this lesson how such things as size, shape, and termination affect waveguide. These properties of waveguide must not be changed or you will get some of the bad effects listed below.

b. For example, if dirt and moisture are allowed to collect inside a section of waveguide, they may change the characteristics of the guide enough to cause considerable loss of power. Also, if waveguide is dented, unwanted reflections may occur and result in a considerable loss of power. If waveguide is dented or terminated improperly, reflections may cause arcing within the guide: So to ensure proper waveguide operation, remember these three rules:

(1) Keep it clean!

(2) Keep it dry!

(3) Don't dent it!

34. Summary.

a. This lesson has explained that a waveguide is and how it works. You have seen how waveguide is tuned and attenuated. You have also learned how to couple waveguide to other RF components.

b. The most important points to remember about waveguide are as follows:

(1) Waveguide is a hollow pipe, usually rectangular, used to guide microwave energy.

(2) Waveguide is a very efficient transmission medium because it has very little loss of energy.

(3) Waveguide is used principally to guide microwave energy to antennas, test equipment, and dummy loads.

(4) A choke joint is a device used to join two sections of waveguide.

(5) Waveguide bends are smooth or mitered.

(6) Twisted waveguide changes the plane of the field within a waveguide.

(7) Flexible waveguide is usually used when a loss of energy can be tolerated.

(8) Waveguide must be tuned to prevent serious reflections.

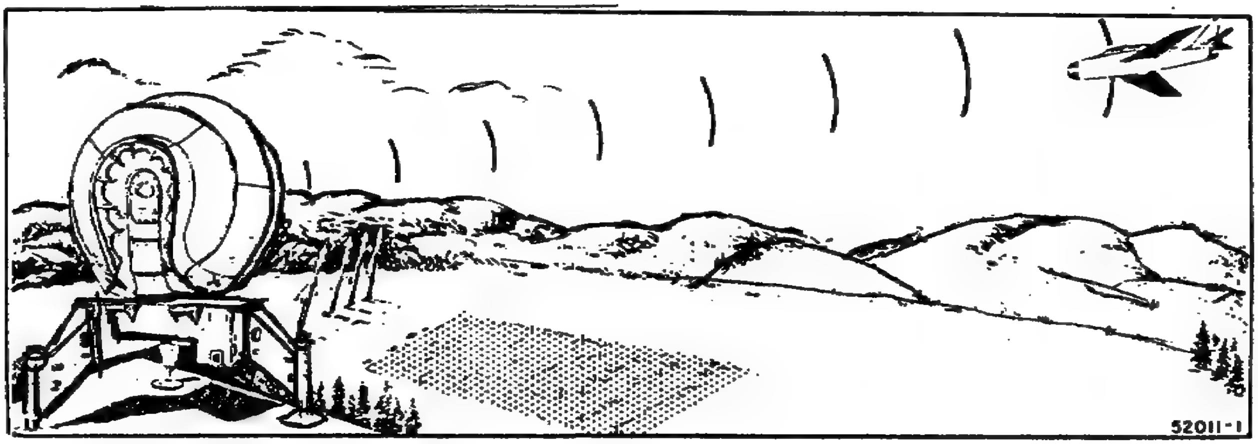
(9) A shutter and resistive card are two types of waveguide attenuators.

Learning Event 2:
RADAR ANTENNAS

1. General.

You know that radar operates on the echo principle. The magnetron generates short regularly-spaced RF pulses when excited by short DC pulses from the modulator. These high-power RF pulses are transmitted into space in a narrow beam from a directional antenna (Figure 131). A target in the path of the radar beam sends back some of the RF energy in the form of echoes. The antenna intercepts these echoes and directs them to a sensitive receiver and finally to the radar indicator.

Figure 131. The Radar Antenna Radiates RF Energy Into Space in the Form of a Narrow Beam.



2. Accuracy depends on antenna directivity and width of radar beam.

a. The radar set determines the range or distance to the target by measuring the time that the RF energy takes to hit the target. This time is measured and displayed on the radar indicator where it is translated instantaneously into yards or miles.

b. The direction of the target in azimuth and elevation is given by the physical position of the antenna system. The antenna rotates in azimuth or tilts back at an angle so that the full strength of the radar beam hits the target. When the antenna points directly at the target, the antenna and radar beam form an angle with the horizontal plane of the earth, giving us the angle of elevation. The antenna and radar beam also point in a certain direction with respect to North, giving us the azimuth angle or bearing. The accuracy of this angular information about target location depends upon the directivity of the antenna and the width of the radar beam.

c. The purpose of this lesson then, is to show why a radar antenna requires a narrow RF beam and how the directivity and gain of the antenna affects the width of the radar beam. To understand more fully how a radar antenna works, we will review some antenna fundamentals. We will begin by defining an antenna.

3. What is an antenna?

a. An antenna is a conductor or system of conductors that radiates and receives electromagnetic energy. In communications systems, an antenna may be very simple. For example, an ordinary broadcast receiver uses just a length of wire. If you want good long distance communications, especially at UHF and microwave frequencies, you have to use a better antenna such as a dipole or even a whole system of dipoles.

b. Radar sets need different types of antennas because radar serves a different function than a communications system. We use radar for searching, tracking, navigation, and height finding. Each one of these applications needs a specific type of antenna. But even though they may be constructed somewhat differently, most radar antennas consist of a feed and reflector. The feed may be a dipole or a horn that couples energy to the reflector.

c. Now let's review what an antenna does.

4. An antenna radiates or picks up energy.

a. You have learned how radar generates an RF carrier and combines information with the carrier. That's the purpose of the transmitter and modulator. You have also learned how the set detects and amplifies a small amount of RF current to provide target information. That's the purpose of the receiver.

b. Antennas serve a dual purpose, they transmit energy and receive energy. A transmitting antenna takes the energy from the transmitter, changes it into electromagnetic waves, and radiates the waves out into space. A receiving antenna picks up the electromagnetic waves and changes them into voltage and current.

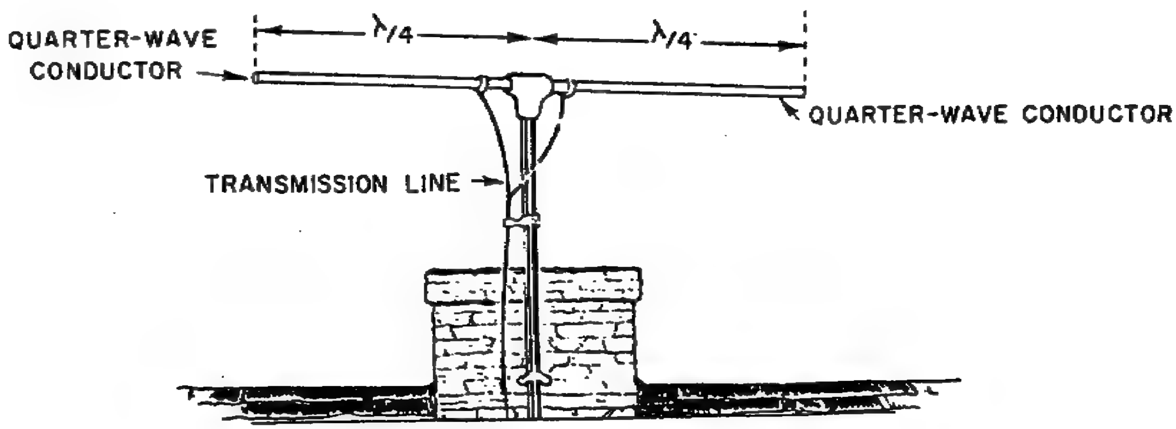
c. Transmitting and receiving energy does not require special types of antennas; any antenna can be use to transmit or receive. In fact, most radar sets use the same antenna to radiate energy from the transmitter, pick up the echoes of this energy, and direct the echoes to the receiver.

d. Now, let's review the operation of a simple dipole antenna.

5. Dipole antennas.

a. You are already familiar with the simple dipole antenna shown in Figure 132. You have seen this type of antenna many times on roof tops; it's one kind of TV antenna.

Figure 132. Simple Dipole Antenna.



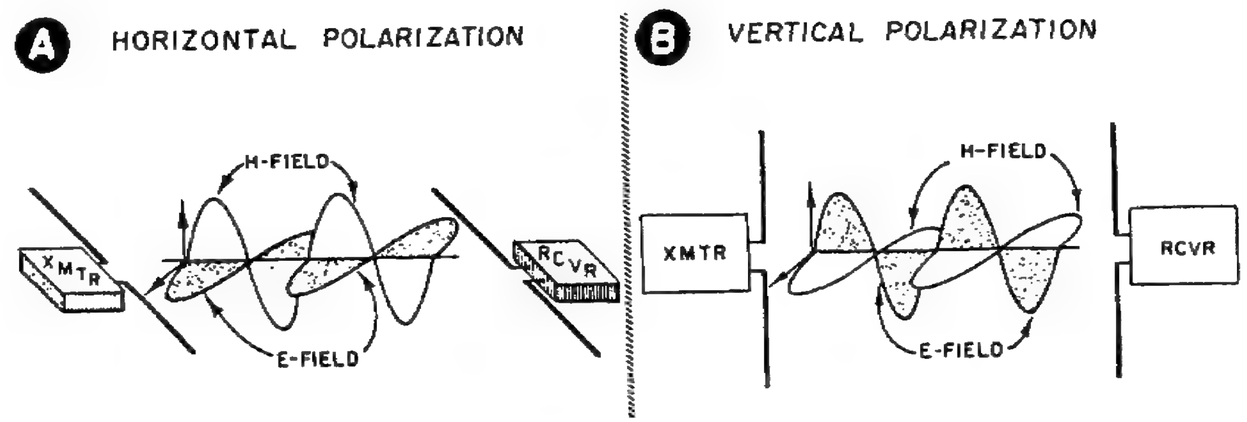
b. You know that a simple dipole antenna consists of two quarter-wave conductors spaced a few inches apart in line with each other. When used as a transmitting antenna, the output of the transmitter feeds to the inside ends of the two conductors. When the transmitter is on, current flows in each conductor. The current flow back and forth in two conductors sets up a magnetic field around them. The magnetic field (H) produces an electric field (E) and the two fields (called the electromagnetic field) radiate into space. You will recall that the plane of the electric field determines how the antenna is polarized.

6. Polarization of a dipole antenna.

a. The electric and magnetic fields radiate from the dipole in the manner shown in Figure 133. The magnetic field always surrounds the conductors and is perpendicular to them; the electric field is parallel to the conductors.

b. In Part A of Figure 133, the conductors of the dipole are horizontal to the earth, and so is the electric field. Therefore, we call this a horizontally polarized antenna. The dipole in Part B of Figure 133 is vertical to the earth, and so is the electric field. Therefore we call this a vertical polarized antenna.

Figure 133. Horizontal and Vertical Polarization.



c. The importance of knowing the polarization of an antenna is this: a receiving antenna usually picks up more energy when it is polarized the same way as the transmitting antenna. That's why all TV receiving antennas are horizontal, because the TV transmitting antennas are horizontal.

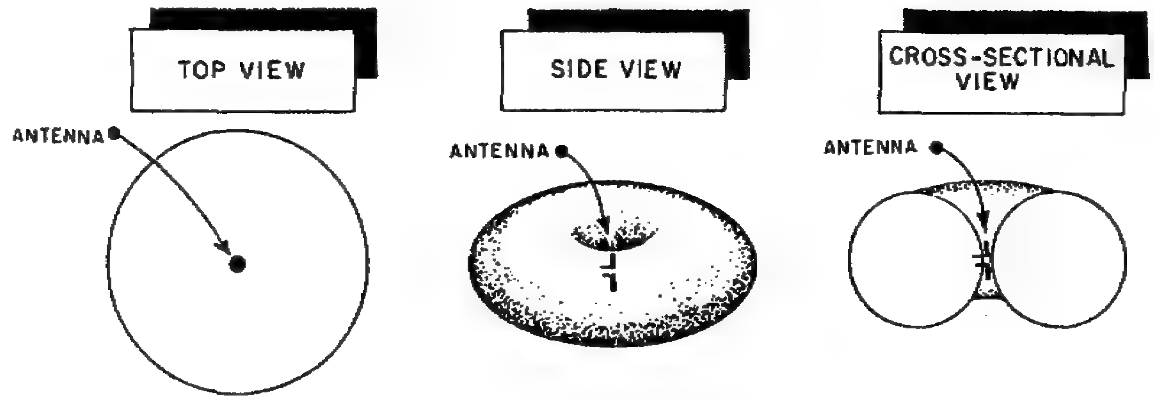
d. That completes the brief review of antenna fundamentals. Now, let's look at some new antenna characteristics. The two main ones that apply especially to radar antennas are directivity and radiation pattern. Both of these antenna properties work together.

7. Directivity and radiation pattern.

a. A directive antenna radiates energy in only one direction and receives energy from only one direction. If the antenna radiates and receives signals in many directions, it has poor directivity. If the antenna transmits and receives signals from only one direction, it has good directivity.

b. Figure 134 shows how energy radiates in all directions from a dipole antenna. The doughnut-shaped pattern shows you the radiation field of a transmitting antenna. When used to represent a receiving antenna, the pattern indicates the areas from which signals will be received. This diagram is called a radiation pattern.

Figure 134. Doughnut Radiation Pattern
of a Simple Dipole.



c. A simple dipole has very poor directivity because it radiates in almost all directions. A simple dipole antenna is used, then, to radiate power in all directions. It is a very efficient antenna for commercial radio and TV stations.

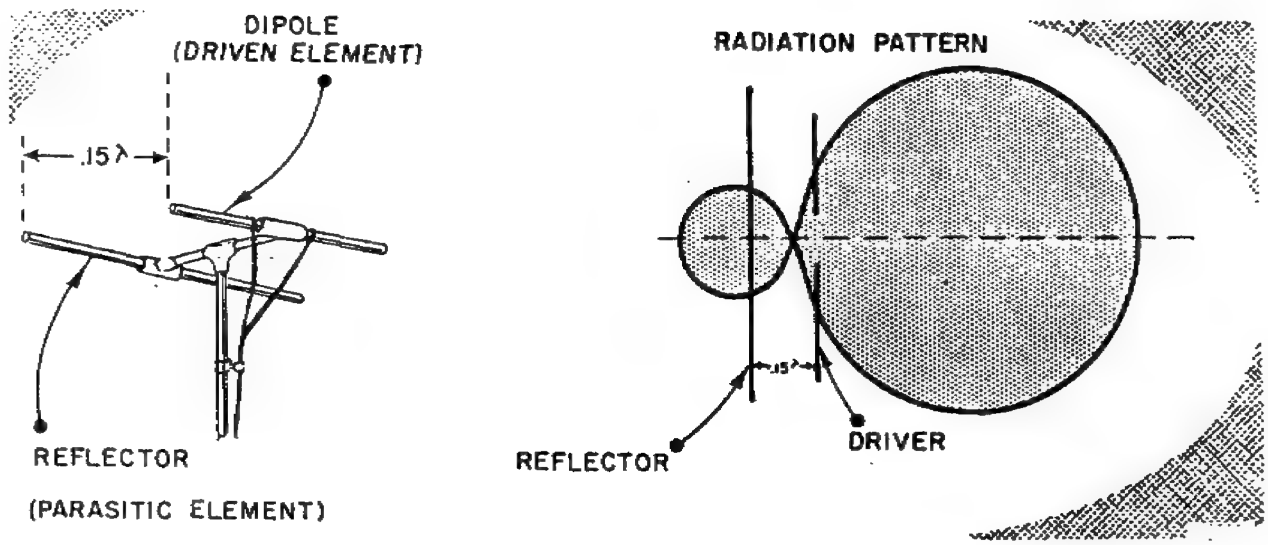
d. Now suppose you want to transmit in only one direction, or you want to receive from only one direction. For example, if you are transmitting to ships out at sea, you want all the power from the transmitter to go out over the ocean. Can you do this using a dipole antenna? Yes, you can, by adding a reflector to the dipole.

8. Adding a reflector to the dipole makes the antenna directional.

a. To make a dipole antenna directional, you merely add an element called a reflector. A reflector may be nothing more than a conducting rod a little longer than one-half wavelength. Figure 135 shows a dipole with a reflector; it also shows the antenna radiation pattern.

b. The elements of an antenna that radiate or receive energy are called driven elements. Any other elements are called parasitic elements. Notice in Figure 135 that the dipole is the driven element, and the reflector is the parasitic element.

Figure 135. Simple Dipole With a Reflector.

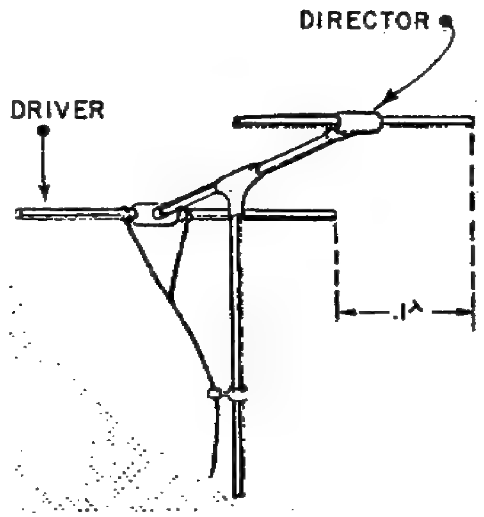


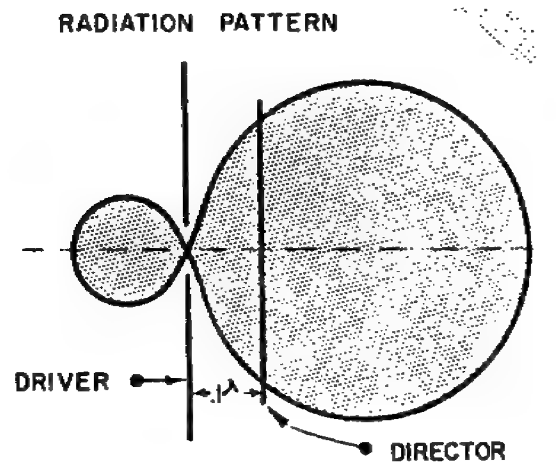
c. The reflector picks up energy from the driven elements and reradiates it. The reflector is placed .15 wavelength from the driven element so that the fields cancel in the direction of the reflector and add in the direction of the drivers. Notice that most of the energy is transmitted in one direction. If this same antenna is used as a receiving antenna, it will pick up energy from the same direction.

9. Adding a director also makes dipole antenna directional.

a. Another way of making a dipole antenna directional is to add a parasitic element called a director to the two conductors as shown in Figure 136. The director is placed .1 wavelength from the driven elements, and it is a little shorter than one-half wavelength. The director picks up energy from the driven elements and reradiates it in such a way that the energy adds to the original radiation in the direction of the director.

Figure 136. Simple Dipole With a Director.



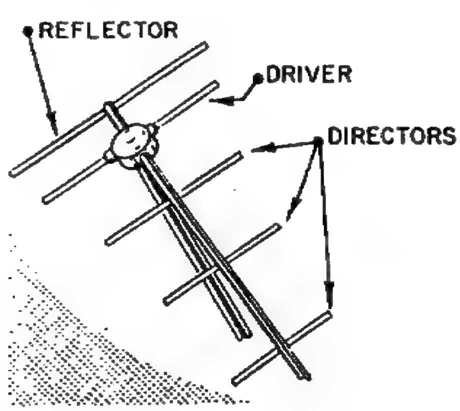


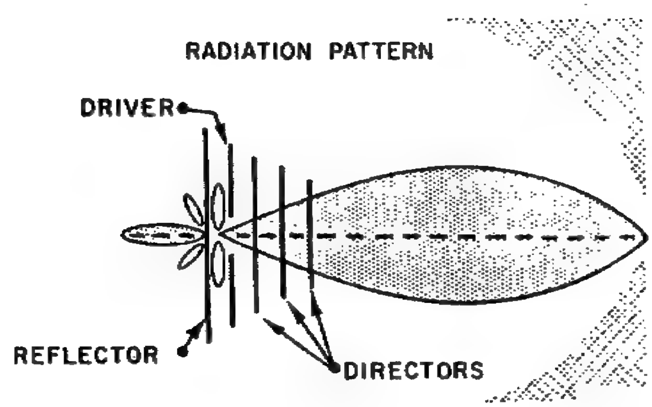
b. Notice that the radiation pattern of a dipole with a director is similar to a dipole with reflector. Now, what will the radiation pattern be if you add both a reflector and a director to the simple dipole?

10. Dipole with director and reflector.

a. Adding both a director and a reflector to a dipole makes the antenna more directional. In fact, the more parasitic elements you add, the more directional the antenna gets. An antenna with several parasitic elements is shown in Figure 137; it's called a YAGI antenna. Notice that the radiation pattern is more directional because of the additional directors.

Figure 137. YAGI Antenna.





b. Now you know what we mean by directivity and radiation pattern. There is one more antenna characteristic you should know about, the gain of an antenna.

11. Antenna gain.

a. An antenna is not an amplifying device, so you do not get a real gain as you do from an amplifier. In other words, if you put two watts into an amplifier that has a gain of 10, you get 20 watts out. If you put two watts into an antenna, it doesn't matter what the gain is; you still cannot get more than two watts out, there is no increase of power.

b. Antenna gain merely tells you how good a certain antenna is as compared to a simple dipole antenna. We use a simple dipole as a standard because it radiates energy in all directions parallel to it. Antenna gain, then, is a measurement of the effectiveness of a directional antenna as compared to that of a simple dipole which is nondirectional. When we make an antenna directional, most of the power it radiates or receives is in one direction.

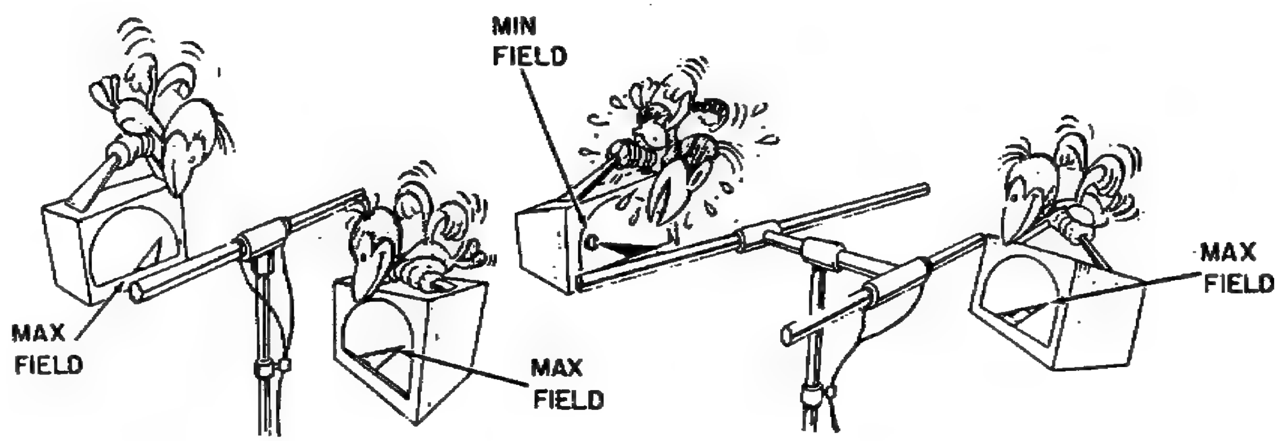
c. The gain of a receiving antenna, therefore, is a comparison between the power absorbed by the antenna from a given signal and the power that would be absorbed by a simple dipole under exactly the same conditions.

d. For example, a receiving antenna with a gain of 10 absorbs about ten times the amount of power as a simple dipole absorbs. For transmitting, an antenna with a gain of 10 needs only one-tenth as much power to produce a given field strength in the desired direction as does the simple dipole. Here's how it works with the antenna you have just learned about.

12. Gain of a dipole with a director or reflector.

a. If you measure the radiated power a certain distance from a simple dipole antenna, as shown in Part A of Figure 138, you will measure the same amount of power in all directions around the antenna. Now, if you measure the radiated power the same distance away from a dipole that has a reflector or a director, as in Part B of Figure 138, here's what happens. You get very low readings in one direction and much higher readings in the opposite direction because the director or reflector concentrates the power in one direction.

Figure 138. Measuring the Power Gain of a Directive Antenna.



b. In other words, if you have two antennas with an equal amount of power coupled to each one, you get more radiated power from the directional antenna than from the nondirectional one. You can see then why we say that an antenna with either a director or reflector has a power gain compared to a simple dipole. Actually, an antenna with either a director or reflector has a gain of about two over a single element dipole. A YAGI antenna has a gain of about five.

13. Summarizing main points so far.

a. An antenna is a conductor or system of conductors that radiates and receives electromagnetic energy.

b. A good transmitting antenna is also a good receiving antenna.

c. Most radar sets use the same antenna to radiate energy from the transmitter, then pick up echoes of this energy, and direct the echoes to the receiver.

d. A simple dipole antenna consists of two quarter-wave conductors and is nondirectional.

e. Adding a reflector makes the dipole antenna directional.

f. A YAGI antenna consists of a driven element, at least one reflector, and several directors.

g. A YAGI antenna radiates most of its energy in one direction and has a gain of about five as compared to a simple dipole.

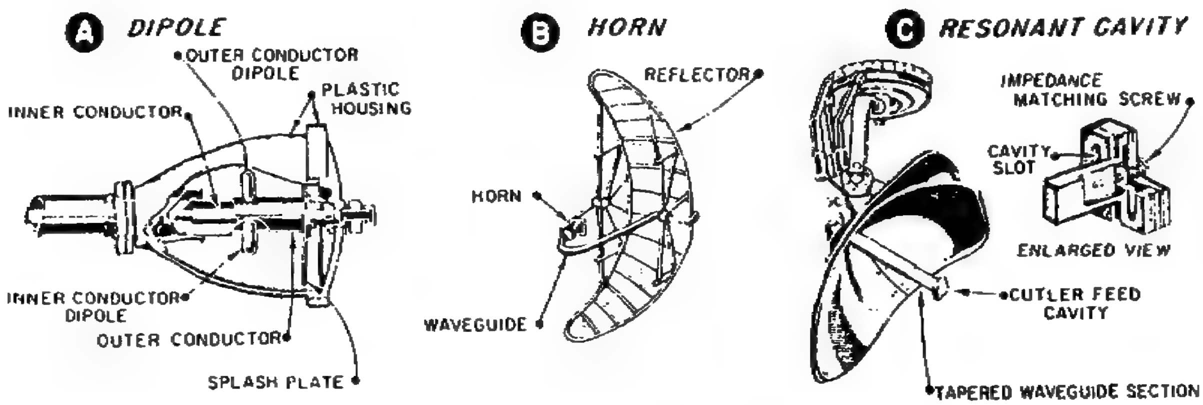
h. A radiation pattern is a diagram that shows you the directivity of an antenna.

14. How energy is coupled to a radar antenna.

a. You know that a radar antenna consists of a feed and a reflector. The feed is the radiating part of the antenna and is used to couple the RF energy to the reflector. It may be a dipole, a horn, or a resonant cavity. Figure 139 shows an example of each type of feed.

b. Part A of Figure 139 shows a dipole used to feed a parabolic reflector. You will learn about parabolic and other types of reflectors later in this lesson. Notice in Part A of Figure 139 that the dipole is connected to a rigid coaxial transmission line. One dipole element is connected directly to the outer conductor of the coaxial line, and the other element is connected to the inner conductor. Each element is one-quarter wavelength long, so that the two together form a half-wave dipole. The splash plate in front of the dipole is a small reflector that directs the front radiation of the dipole back to the main dish reflector.

Figure 139. Types of Antenna Feeds.



c. Horn-type feed in shown in Part B of Figure 139. It consists of a waveguide with the open end flared to form a horn. The reason for flaring the end of the waveguide is to match the impedance of the waveguide transmission line to the impedance of free space. This provides a maximum transfer of energy from feed to reflector. Horn-type feed is used primarily in the higher radar frequency bands, such as the 3 cm band.

d. An example of resonant cavity feed is shown in Part C of Figure 139. In this method, called cutler feed, the waveguide transmission line terminates in a tunable resonant cavity. You tune the resonant cavity using the adjustable screw in the rear. RF energy comes out of the cavity through the two slots in the front and bounces off the reflector as it did with the other feed methods.

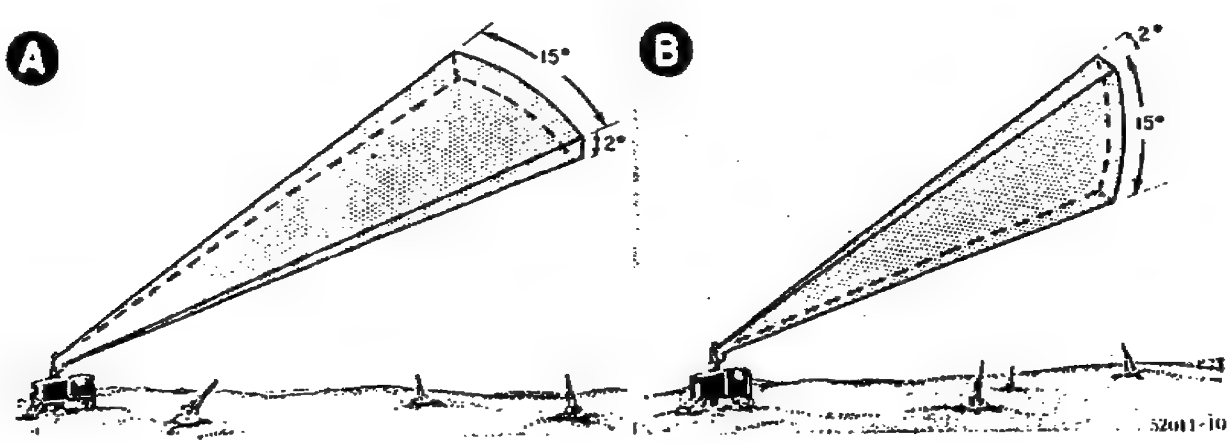
e. Now you know how RF energy is fed to the reflector. Next, let's find out how the reflector forms the RF energy into a beam.

15. Antenna radiation pattern is called a beam.

a. You know that the light directed from a flashlight is called a beam; so is the energy radiated from a radar antenna. The width of a radar beam is measured in degrees in two directions, horizontally (parallel to the earth), and vertically (perpendicular to the earth). Figure 140 shows you the beamwidth of two antennas.

b. The antenna in Part A of Figure 140 has a vertical beamwidth of two degrees and a horizontal beamwidth of fifteen degrees. Because of these dimensions, we say the beam is narrow vertically and broad horizontally.

Figure 140. Broad and Narrow Radar Beams.



c. The other antenna in Part B of Figure 140 has a horizontal beamwidth of 2 degrees and vertical beamwidth of 15 degrees. Therefore, we say this antenna has a beam that is narrow horizontally and broad vertically.

b. Right about now you are probably wondering what all this has to do with radar antennas. Well, all radar antennas need a beam that is narrow in at least one direction. So, the type of beam we need determines the type of antenna used.

16. Why radar needs a narrow beam.

a. A radar indicator gives you at least one of the following three kinds of information:

(1) Range.

(2) Azimuth.

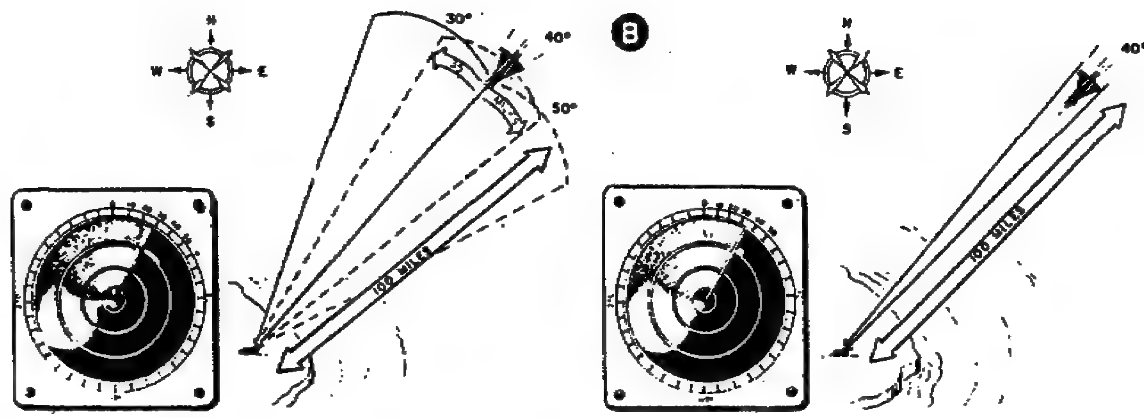
(3) Elevation.

b. The accuracy of the azimuth and elevation information depends upon how narrow the beam is.

17. A narrow horizontal beam gives accurate azimuth information.

a. To provide accurate azimuth information, the radar set must send out a narrow horizontal beam. You can see why by comparing the two radar search sets in Figure 141. The set in Part A of Figure 141 has a broad horizontal beam. Therefore, the set picks up echoes from an enemy jet bomber even when the antenna is pointed in a direction 10 degrees away from the target. The operator of the set knows only that the bomber is somewhere between 30 to 50 degrees east. At a range of 100 miles, the distance between 30 and 50 degrees is about 35 miles. If fighters are sent out to intercept the jet, they have to look for it in this 35-mile area. Considering the speed of a jet, the enemy plane can cause considerable damage before the fighter planes find it. Because the beam is so broad, the azimuth information is just not accurate enough.

Figure 141. Broad and Narrow Horizontal Beams.



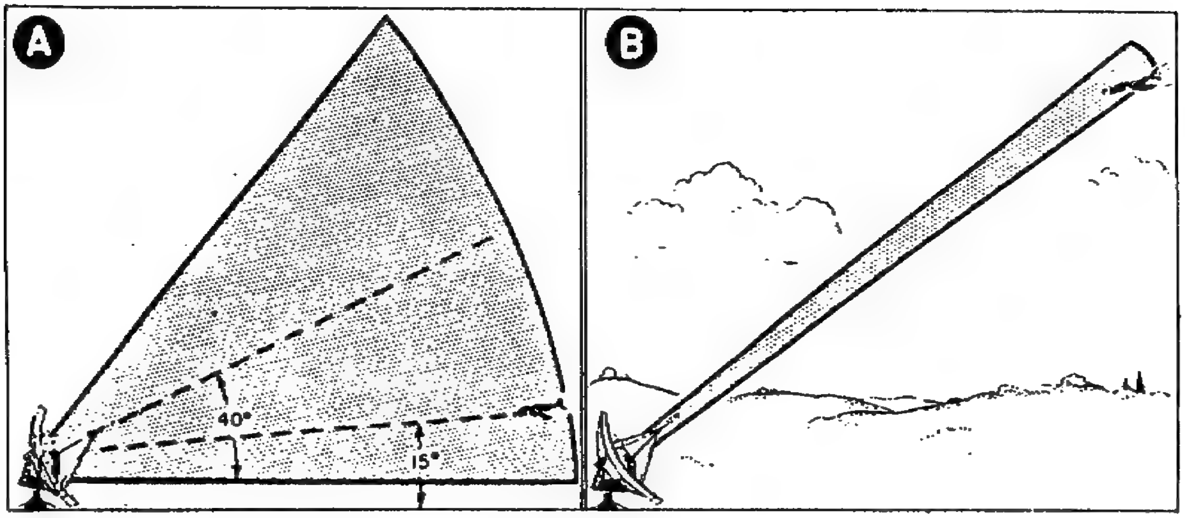
b. Now notice in Part B of Figure 141 how a narrow horizontal beam gives more accurate azimuth information. The indicator tells the operator that the bomber is exactly 40 degrees east. Fighters directed to intercept an enemy jet using information from this set can head straight toward the target.

c. Remember, then, that a radar set must have a narrow horizontal beam to give accurate azimuth information.

18. A narrow vertical beam gives accurate height information.

a. To provide accurate elevation information, the radar set must have a narrow vertical beam. You can see the reason by comparing the two height-finding sets shown in Figure 142. Notice that the set in Part A of Figure 142 sends out a broad vertical beam. The beam is so broad that even when the antenna is pointed at an angle of 40 degrees, it picks up a plane that is at an angle of 15 degrees. The operator of the set knows, of course, that the enemy plane is there, but is not able to determine the exact height. If this information is used to aim and fire antiaircraft guns automatically, the guns will miss the target because of the inaccurate information.

Figure 142. Broad and Narrow Vertical Beams.



b. By using a narrow vertical bean as in Part B of Figure 142, we get accurate information on target elevation. Now, as soon as the set picks up a target, the antenna aims directly at the target.

c. Some radar sets need a beam that is narrow both vertically and horizontally. For example, a tracking radar like radar set M-33 must give accurate information on both azimuth and elevation. Therefore, the beam sent out by the M-33 antenna must be narrow both vertically and horizontally.

19. The main points to remember about radar beams.

a. Radar beamwidth is measured in degrees, horizontally and vertically.

b. A narrow horizontal beam gives accurate azimuth information.

c. A narrow vertical beam gives accurate elevation information.

d. A beam that is narrow both vertically and horizontally gives accurate information on both azimuth and elevation.

e. Search radar sets have a narrow horizontal beamwidth.

f. Height-finding radar sets have a narrow vertical beamwidth.

g. Tracking radar sets have a beam that is narrow both vertically and horizontally.

20. Reflectors are used with radar antennas to produce correctly shaped beams.

a. Radar sets operate in the microwave region of the frequency spectrum. Microwave frequency wavelengths are so small that they act like light waves. That's why most sets use antenna reflectors that work like light reflectors. There are four main types of antennas that you will work with, as follows:

(1) Paraboloid (dish)

(2) Orange peel.

(3) Parabolic cylinder.

(4) Metallic lens.

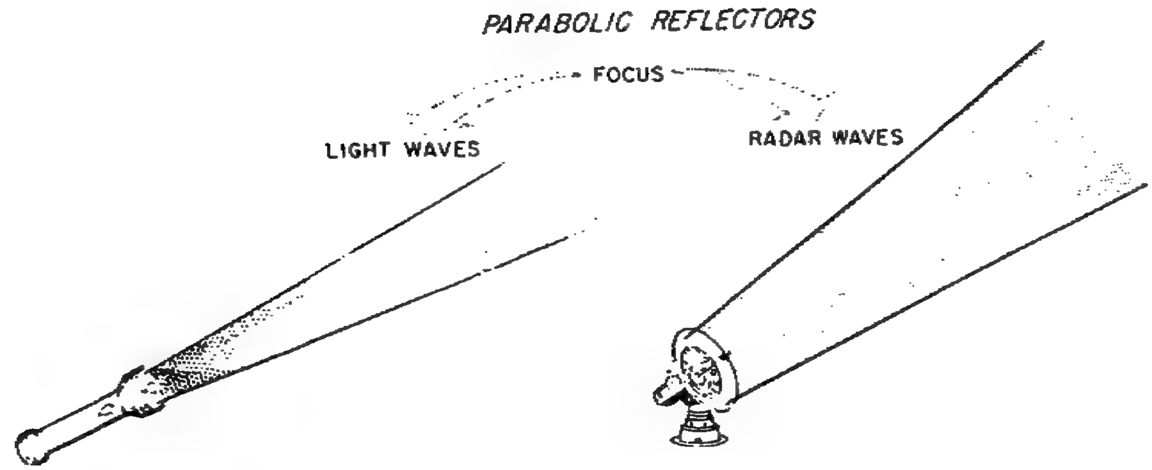
b. The first three types of antennas get their names from the shape of their reflectors. The metallic lens type is actually a lens made of metal.

21. Radar reflectors work like light reflectors.

a. Take a look at a flashlight and notice the reflector surrounding the bulb. The reflector concentrates light from the bulb into a narrow beam. Similarly, a radar reflector concentrates RF energy from the antenna into a narrow beam as shown in Figure 143.

b. Without a reflector, light from the flashlight bulb would go out in all directions, and so would RF energy from the antenna.

Figure 143. How a Radar Reflector Works.

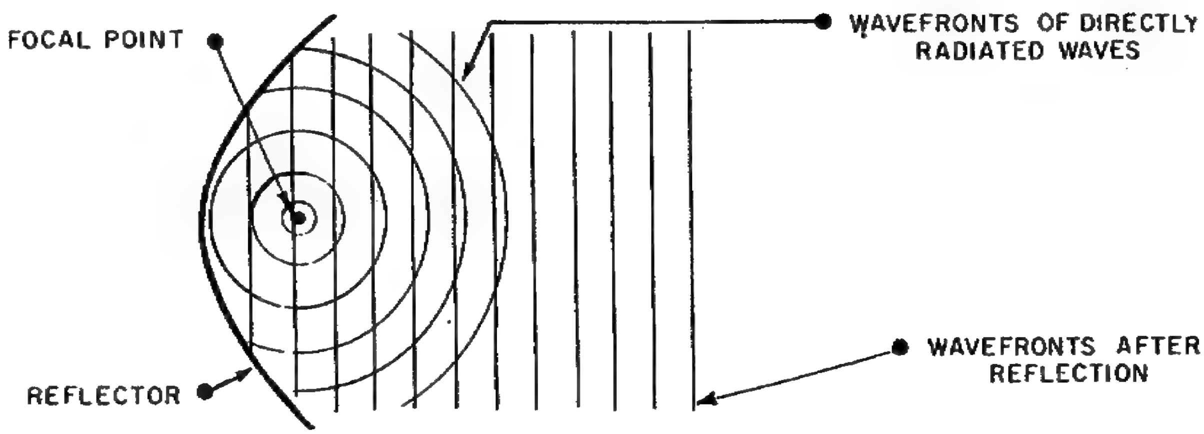


c. The antenna in Figure 143 uses a reflector having the geometric shape of a paraboloid. Because a paraboloid looks something like a dish, it is commonly called a dish reflector.

22. How a dish reflector works.

a. Figure 144 gives a cross-sectional view of a dish reflector. Notice the point in front of the reflector called the focal point. The focal point is important because any energy radiated from the focal point strikes the reflector and bounces off in a straight line away from the reflector. So, by locating the antenna at the focal point, we can feed RF energy at the focal point and get a narrow cone-shaped beam. The beam, of course, is very directional. That's why an antenna using a dish reflector has a gain of about 1,000 over a simple dipole antenna. Because of their directivity and high gain, dish-type reflectors are used with radar sets that track targets.

Figure 144. How a Paraboloid Works.



b. Dish reflectors are usually made of wire mesh or from solid material, with small holes to make them lighter and to reduce the amount of surface exposed to the wind. The holes have very little effect on reflector operation as long as they are small compared to the wavelength of the RF. Some radar sets use just a section of a dish as a reflector.

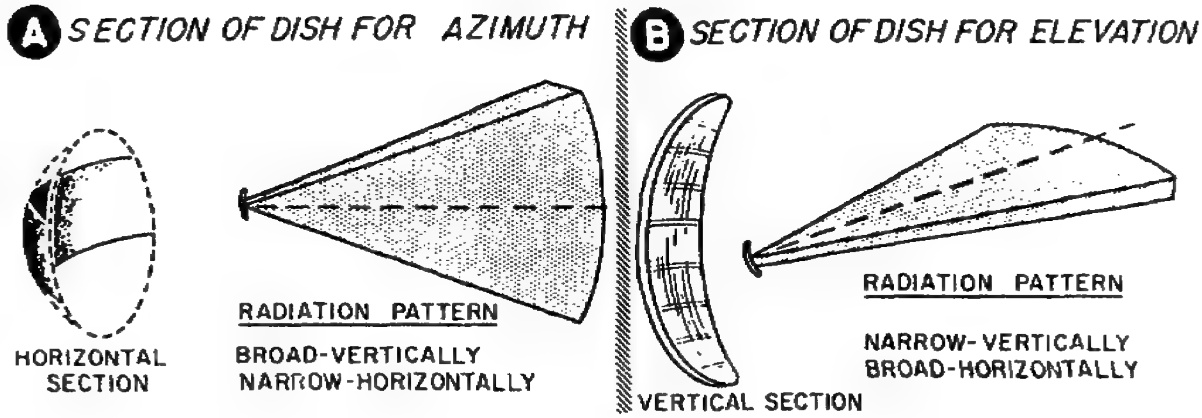
23. A section of a dish reflects energy in a fan-shaped pattern.

a. If you feed RF energy to just a section of a dish like the one in Part A of Figure 145, you get a radiation pattern that looks like a fan. The beam is still sharp horizontally, but it is broad vertically because there is less reflector surface to concentrate the beam in that plane. This type of reflector is used with search radar sets for two reasons:

(1) The narrow horizontal beamwidth gives accurate azimuth information.

(2) The broad vertical beamwidth allows the set to pick up targets at any altitude.

Figure 145. How a Section of a Dish Works.



b. Now, if you turn the reflector around 90 degrees as shown in Part B of Figure 145, the beam also turns 90 degrees. This means the beam is sharp vertically, but broad horizontally. This type of reflector is used with height-finding radar sets for two reasons:

(1) The narrow vertical beamwidth gives accurate elevation information.

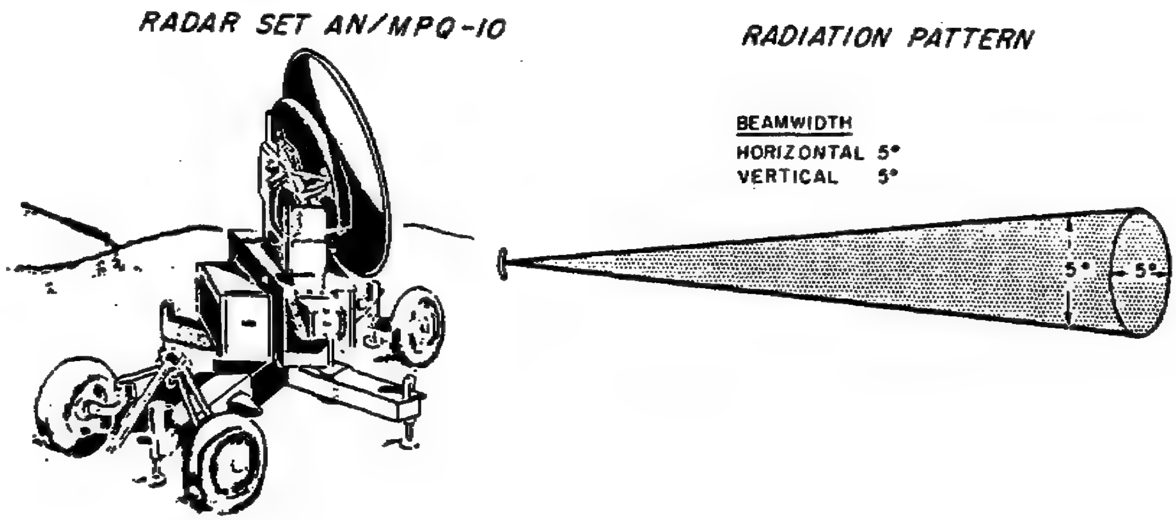
(2) The broad horizontal beamwidth allows the set to cover a fairly wide area without rotating.

c. You have seen how we get different beam patterns by using reflectors of various shapes. Now, let's find out about some of the specific antennas.

24. Radar set AN/MPQ-10 uses a dish reflector.

a. Figure 146 shows the AN/MPQ-10 radar antenna and its radiation pattern. The MPQ-10 radar set locates and tracks mortar and artillery shells. Therefore, it uses a dish reflector to produce a narrow cone-shaped beam. Notice that both the horizontal and vertical beamwidths are the same, 5 degrees.

Figure 146. Radar Set AN/MPQ-10 Antenna.



b. RF energy is carried to the antenna by a rigid coaxial transmission line that goes through the center of the reflector. The coaxial line terminates at the dipole feed in front of the dish. The dipole is located at the focal point of the paraboloid. Radar set AN/MPQ-10 uses the same dipole feed already described and illustrated in Figure 146.

c. The paraboloid reflector focuses the RF pulses radiated by the dipole antenna into a narrow cone-shaped beam. The reflector also focuses the received target echo pulses on the dipole antenna, thereby increasing the intensity of the received pulses.

d. Now, let's look at a reflector that is just a section of a dish.

25. Radar set 4N/SPN-5 uses an orange peel reflector.

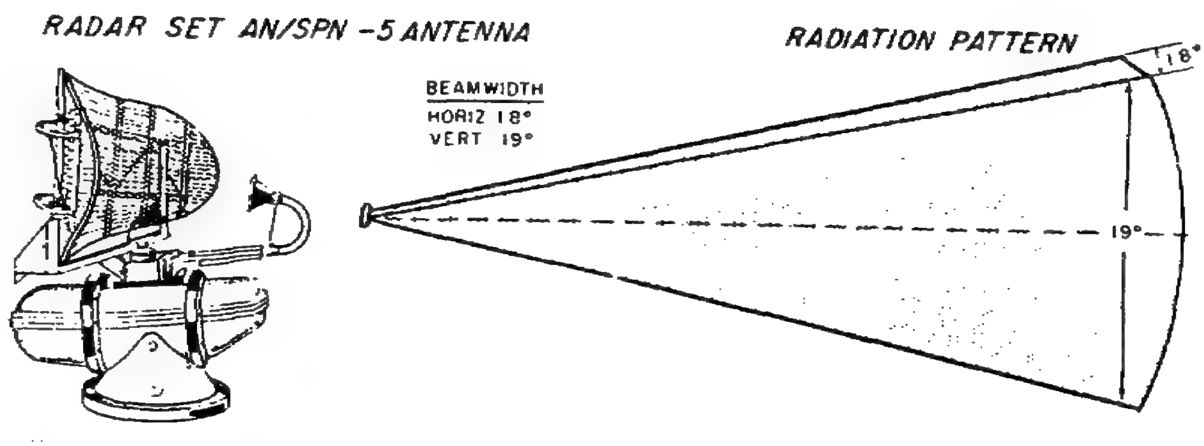
a. Figure 147 shows the AN/SPN-5 radar antenna and its fan-shaped radiation pattern. The AN/SPN-5 is a navigational radar used on many types of boats and ships. For navigational purposes, the antenna must send out a beam that is narrow horizontally and broad vertically. To get the correct beamwidths, the set uses a section of dish reflector. We call the reflector an orange peel because of its shape.

b. The orange peel produces the fan-shaped radiation pattern shown. The short height of the reflector makes the beam broad vertically, and the long width makes the beam narrow horizontally. The narrow horizontal beamwidth gives

the set accurate azimuth information. The broad vertical beamwidth lets the set pick up targets even when the ship pitches and rolls.

c. Notice that the orange peel reflector is not solid; it is made of metal tubes. This type of construction keeps down the overall weight of the antenna and prevents high wind resistance. Weight and wind resistance are very important considerations in marine and aircraft applications of radar.

Figure 147. Antenna Used in Radar Set AN/SPN-5.

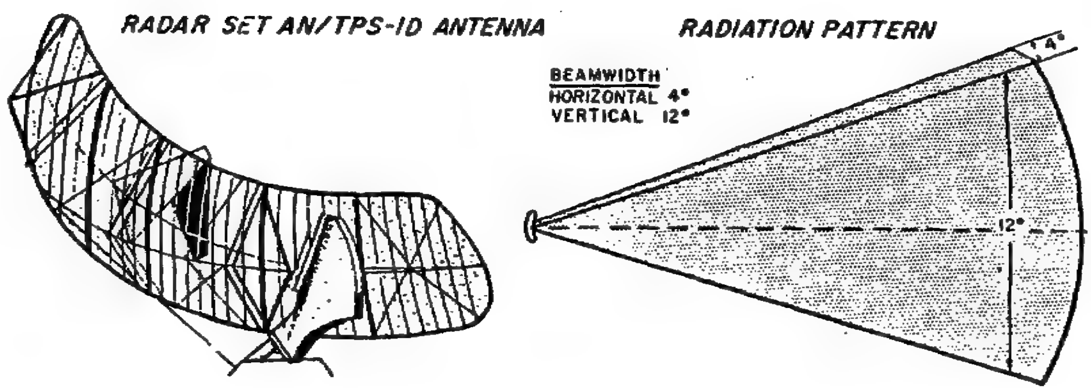


d. Notice in Figure 147 how the set feeds RF energy to the orange peel reflector. Waveguide carries the RF pulses up from the magnetron. The waveguide terminates at the focal point of the reflector in a horn. The horn matches the impedance of the waveguide to the air. Although you can't see it in the illustration, the horn has a plastic cover over its opening. The plastic cover protects the inside of the waveguide from bad weather and sea spray.

26. Radar set AN/TPS-1D also uses an orange peel reflector.

a. Radar set AN/TPS-1D is a medium-range radar used primarily as a search radar in detecting aircraft. It uses an orange peel reflector fed by a horn-type feed (Figure 148). The radiation pattern, like that of the AN/SPN-5, is narrow in azimuth and broad in elevation. An antenna with this type of reflector is very useful for aircraft search because the radiation is broad enough in the vertical plane to cover almost all altitudes at the same time.

Figure 148. Radar Set AN/TPS-1D Antenna.

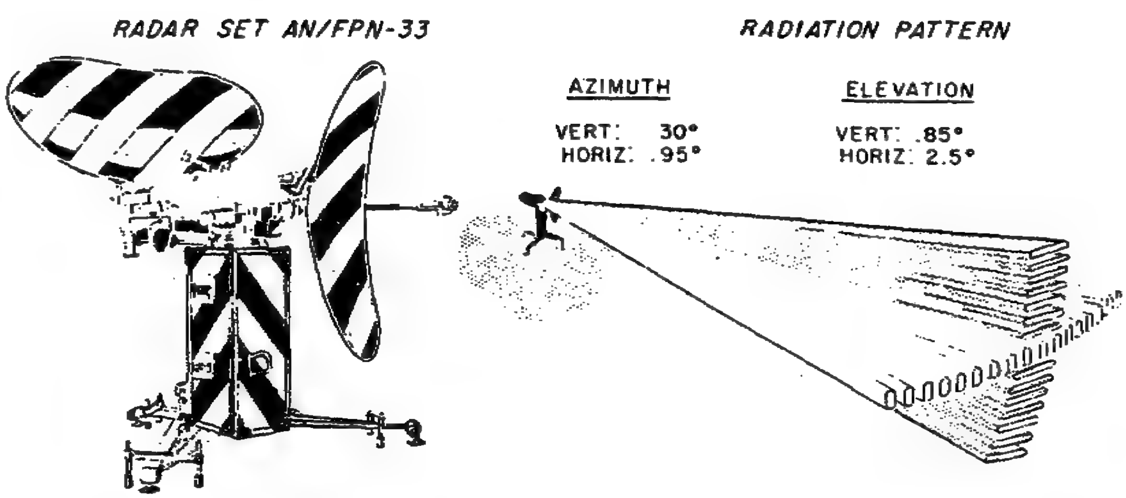


b. Orange peel reflectors are also used to determine the altitude of planes.

27. Radar set AN/FPN-33 uses an orange peel reflector mounted vertically.

a. Figure 149 shows the height-finder antenna of radar set AN/FPN-33 and its radiation pattern. The FPN-33 radar set is used to guide planes to a safe landing when there is no visibility. The set actually uses two antennas; one for azimuth and one for height (elevation).

Figure 149. Radar Set AN/FPN-33 Antenna.



b. The AN/FPN-33 height-finding antenna is similar to the AN/SPN-5 antenna. The big difference between the two antennas is the way their reflectors are mounted. Notice in Figure 149 that the AN/FPN-33 height-finding reflector is mounted vertically to provide a narrow beamwidth. Remember that the antenna must have a narrow vertical beamwidth to give accurate elevation information.

c. The AN/FPN-33 uses waveguide to carry the RF pulses from the magnetron to the reflector. The waveguide terminates at the focal point in a horn. This horn has a plastic cover to protect the waveguide from bad weather and moisture. The gain of this antenna is about 8,000 over a simple dipole.

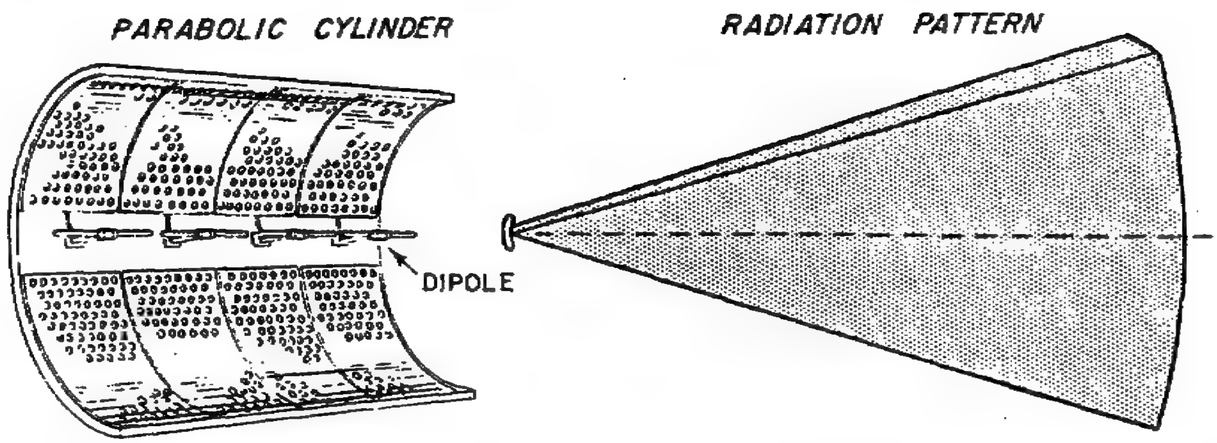
d. A third type of antenna that you will work with has a reflector called a parabolic cylinder.

28. Parabolic reflectors.

a. A spherical wavefront spreads out as it travels, producing a pattern that is neither too sharp nor too directive. A plain wavefront does not spread out because all of the wavefront moves forward in the same direction. For a sharply defined radar beam, the need exists to change the spherical wavefront from the antenna into a plain wavefront. A parabolic reflector accomplishes this.

b. Radio waves behave similarly to light waves. Both microwaves and light rays travel in straight lines and are focused and/or reflected. Figure 150 shows a point-radiation source placed at the focal point. The field leaves this antenna with a spherical wavefront. As each part of the wavefront reaches the reflecting surface, it shifts 180 degrees in phase and moves outward at angles causing all parts of the field to travel in parallel paths. Because of the shape of a parabolic surface, all paths from the focal point to the reflector and back to line XY are the same length. Therefore, all parts of the field arrive at line XY the same time after reflection.

Figure 150. Parabolic Cylinder Reflector.



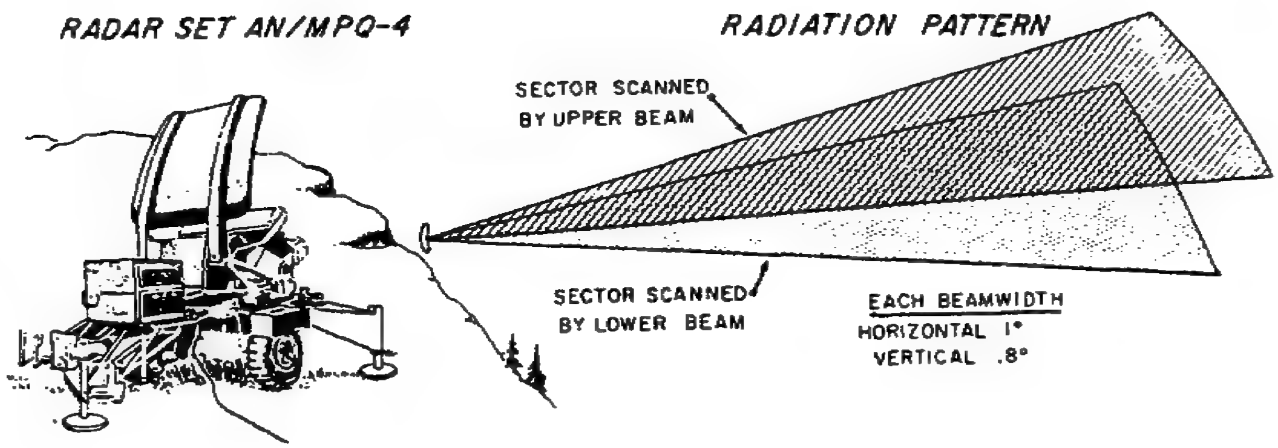
c. There is radiation from the antenna into space as well as toward the reflector when using a dipole as the source of radiation. Energy not directed toward the paraboloid has a wide-beam characteristic that destroys the narrow pattern from the parabolic reflector. Using the hemispherical shield that directs most radiation toward the parabolic surface, prevents this occurrence. This eliminates direct radiation, makes the beam sharper, and concentrates power in the beam. Without the shield, some of the radiated field leaves the radiator directly. Since it is not reflected, it does not become a part of the main beam and serves no useful purpose. The same is accomplished using a parasitic array that directs the radiated field back to the reflector, or using a feed horn pointed at the paraboloid.

d. The radiation pattern of a parabola contains a major lobe directed along the axis of revolution and several minor lobes as shown in Figure 151. Very narrow beams are possible with this type of reflector.

29. Radar set AN/MPQ-4A antenna uses a parabolic cylinder.

Figure 151 shows a radar antenna and its radiation pattern. Radar set AN/MPQ-4A locates mortar and artillery shells, so, the antenna must send out a narrow beam. Actually, this set has two beams. Each beam has a vertical beamwidth of 0.8 degrees and a horizontal beamwidth of 1 degree. Notice that the reflector is a parabolic cylinder fed along a line instead of at one point. Waveguide carries RF pulses from the magnetron to the reflector. The pulses are then fed to the reflector from a horn that runs the length of the reflector.

Figure 151. Radar Set AN/MPQ-4A Antenna.



30. Summary of parabolic reflector antennas.

a. Most radar sets use an antenna with some type of parabolic reflector.

b. A dish reflector concentrates the energy into a narrow cone-shaped beam.

c. An orange peel reflector concentrates the energy into a beam narrow in one plane and broad in the other plane.

d. Radar reflectors are usually fed with a dipole, a horn, or a resonant cavity.

e. The following table (Figure 152) lists the applications of parabolic reflectors.

Figure 152. Parabolic Reflector Applications.

TYPE OF REFLECTOR	PURPOSE
Paraboloid (dish)	Tracking
Orange Peel	Search and height-finding
Parabolic Cylinder	Search

f. Another type of antenna you will work with has a metal lens instead of a reflector. This antenna is used for search and tracking systems.

31. Metallic lens antennas.

a. Some of the newer radar equipment uses the metallic lens antenna. A metallic lens antenna has even more gain and directivity than a reflector type antenna. These antennas do not use reflectors to direct the RF energy. Instead, the energy is directed through an array of parallel metal plates that acts like a lens. The mechanical construction of a metallic lens consists of the following three parts:

(1) A waveguide which brings the energy from the transmitter.

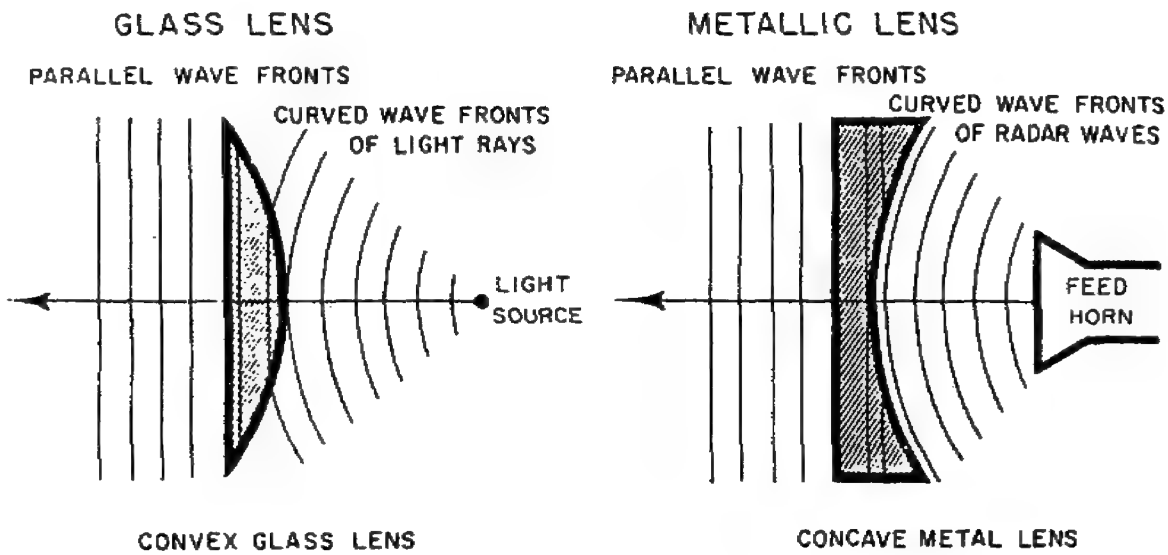
(2) A horn which matches the impedance of the waveguide to air.

(3) A metallic lens which focuses the radiated energy into a highly directional beam.

b. The theory of lens antennas is based on the similarity of radar waves to light waves. You learned how a parabolic reflector focuses RF energy into a highly directive radar beam. The action is like that of a reflector in a flashlight. The action of a metallic lens, on the other hand, is similar to the action of light waves passing through a glass lens such as used in eyeglasses and cameras. Figure 153 compares the glass lens with the metallic lens.

c. Part A of Figure 153 shows the curved wave fronts of light rays striking a convex glass lens. Notice that the light waves coming out of the lens are straight and parallel. The reason is that light travels more slowly in glass than in air. So, the center of the wave fronts are slowed down more than their edges because there is less glass for them to travel through at the edges.

Figure 153. Comparison of Action of Glass Lens to That of Metallic Lens.

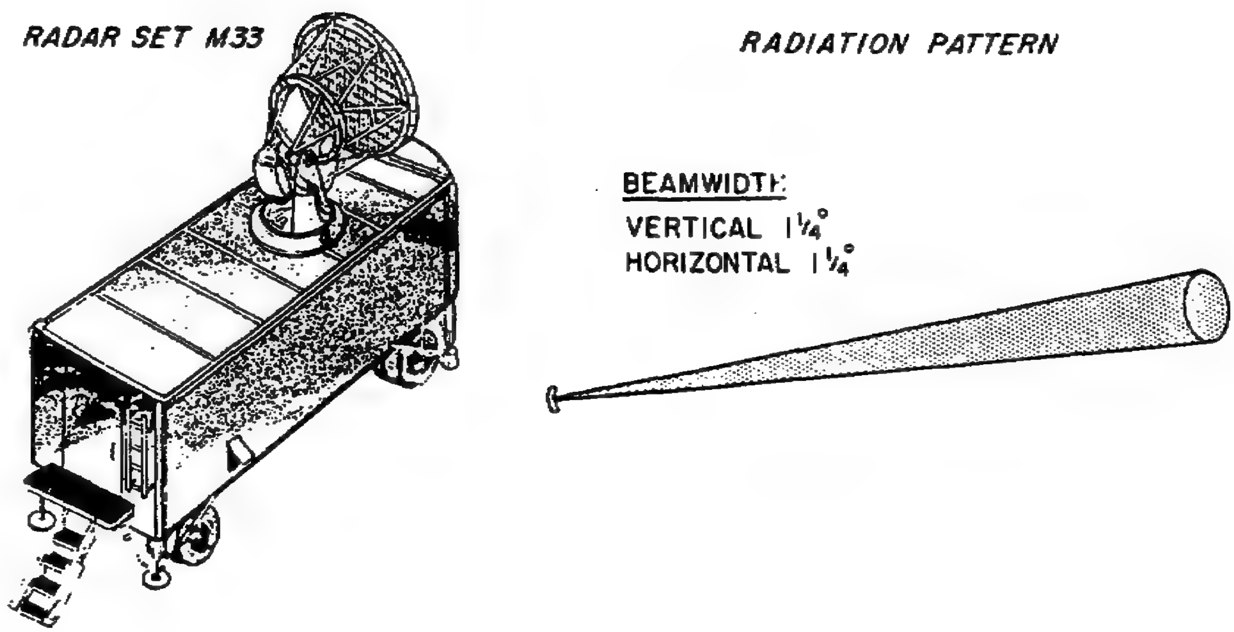


d. In the case of short radar waves, however, the antenna lens must be concave rather than convex. Part B of Figure 153 shows the curved wavefronts of the RF energy radiating from the horn feed and striking the concave lens. The radar waves are straight and parallel as they come out of the lens just like light waves coming through the glass lens. The reason is that the parallel plates of the antenna lens act like waveguides to increase the phase velocity of the RF energy. The longer the waveguide, the greater is the increase in phase velocity. So, the phase velocity of the RF energy is increased more at the edges of the lens than at the center. This results in parallel wavefronts as the RF energy comes out of the lens.

32. The M-33 tracking radar uses a metallic lens antenna.

Figure 154 shows the M-33 tracking antenna and its narrow cone-shaped beam pattern. The vertical and horizontal beamwidth is 1-1/4 degrees and the antenna has a gain of about 10,000 over a simple dipole. One disadvantage of a metallic lens antenna is that it is usually more bulky and heavier than a comparable antenna with a reflector.

Figure 154. M-33 Metallic Lens Antenna.



33. Final summary.

a. This lesson has explained the purpose of an antenna and the reasons why there are so many kinds. As an ATC systems, subsystems, and equipment repairer, you will probably work with the types of antennas covered in this lesson.

b. Remember that antennas are mechanically strong. If you keep them clean and dry, and don't dent them, they won't need repairing. When you have to replace a part, make sure you use an exact duplicate to ensure proper impedance matching and transfer of energy.

c. Here again is a list of the most important points covered in this lesson.

(1) Target location in azimuth and elevation is given by the physical position of the antenna.

(2) Radar antennas must be highly directional so that they can give accurate angular information.

(3) A radar antenna consists of a reflector and a feed.

(4) RF energy is fed to the reflector by means of a dipole, horn, or resonant cavity.

(5) The shape of the reflector depends upon the function of the radar.

(6) A parabolic or dish antenna, used with tracking radars, focuses the RF energy into a narrow cone-shaped beam.

(7) Parabolic cylinders and orange peel antennas are used with search and height-finding radars.

(8) An orange peel antenna used for search has a radiation pattern that is narrow in azimuth and broad in elevation.

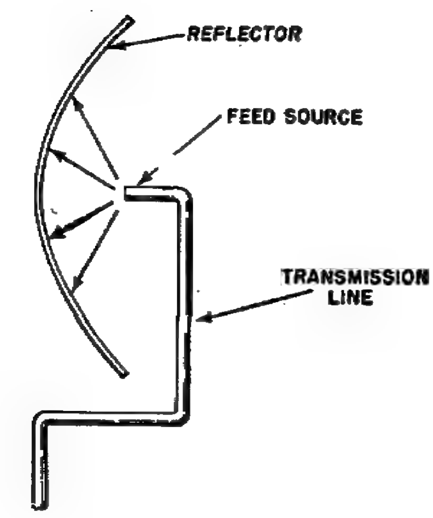
(9) An orange peel antenna used for height-finding has a radiation pattern that is narrow in elevation and broad in azimuth.

(10) A metallic lens is used with search and tracking radars.

34. Reflector feed systems.

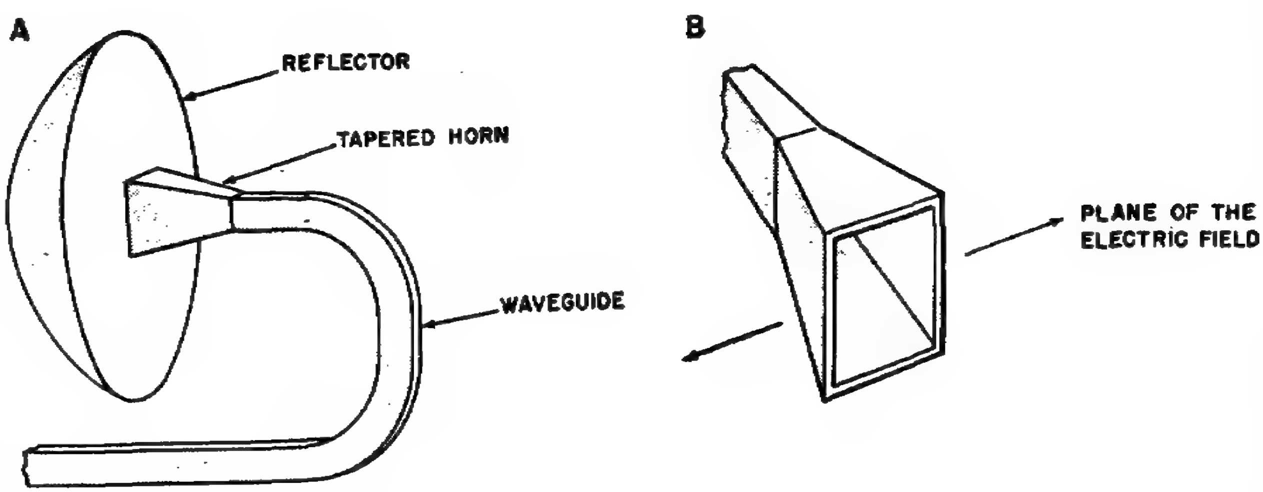
a. Conventional front feeds. In a front feed system, the transmission line (rigid coaxial line or waveguide) is led around the edge of the antenna to the front, where it is terminated by a radiating device as shown in Figure 155.

Figure 155. Front Feed System.



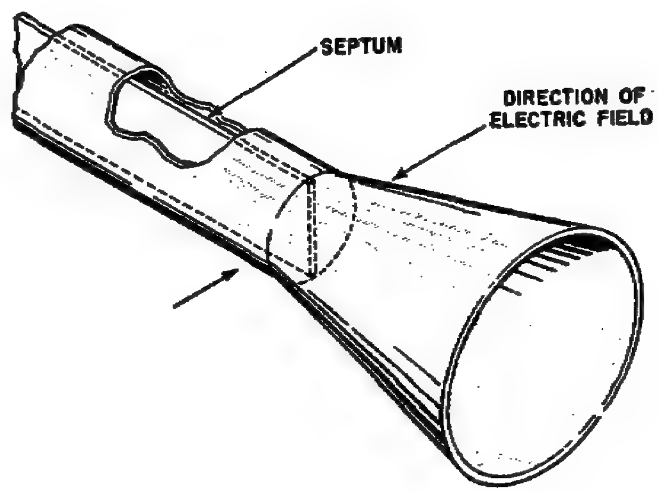
(1) Tapered horn. The ordinary front feed system is nothing more than a tapered horn several wavelengths long. It acts as a tapered impedance matching section that minimizes the mismatch between the impedance of space and that of the waveguide. It also allows the small waveguide, the dimensions of which are fixed by the necessity of avoiding operation in undesired modes, to feed a rather large two-dimensional source. A tapered horn feeding a paraboloid of revolution is shown in Part A of Figure 156 and the horn itself is shown in Part B of Figure 156. The system shown in the illustration is arranged to radiate horizontally polarized signals, as may be seen from the fact that the narrow dimension of the waveguide is horizontal. The open end of the horn, which acts as a two-dimensional source, is located at the focal point of the paraboloid. The dimensions of the open end of the horn are chosen to obtain the desired radiation pattern, which will distribute energy uniformly over the reflector with a minimum loss of power.

Figure 156. Tapered Horn.



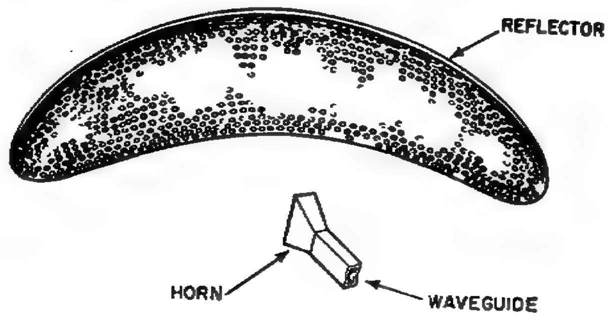
(2) Circular horn. Occasionally, to obtain more uniform illumination of the reflector, a horn with circular cross section is used. This is ordinarily fed by a circular waveguide. A septum, or conducting partition, is inserted in the circular waveguide to control the plane of polarization. This operates by absorbing all signals having electric fields parallel to the surface of the septum. The horn shown in Figure 157 radiates only horizontally polarized signals.

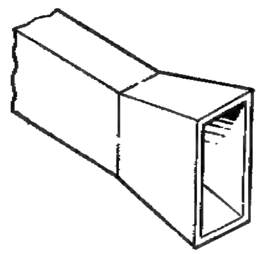
Figure 157. Circular Horn Fed by Circular Guide With Septum.



(3) Sectoral horn. A sectoral horn is used to feed the orange peel reflector shown in Part A of Figure 158. The horn itself is shown in Part B of Figure 158. As before, the open end of the horn acts as a two-dimensional source. Because the opening is quite high, the radiation pattern of the horn is compressed vertically, although it remains wide in the horizontal direction because of the small width of the horn opening. The resulting radiation pattern just fills the orange peel reflector.

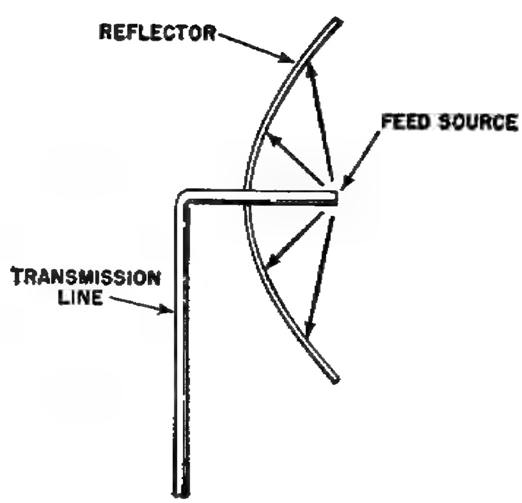
Figure 158. Sectoral Horn.





b. Conventional rear feeds. In a rear feed, the transmission line is passed through the reflector from the rear as shown in Figure 159.

Figure 159. Rear Feed.



(1) Dipole. The usual rear feed is a dipole fed by radiation from a waveguide and a reflector as shown in Figure 160. The waveguide is tapered slightly to obtain and approximate impedance match to the dipole which it feeds. The dipole, which is simply a half-wave antenna, is supported on the septum that extends from the end of the waveguide. The energy radiated from the dipole is reflected back toward the main reflector by a small reflector called a splash plate. The splash plate is sometimes replaced by another radiating element as shown in Figure 161. The radiation from the waveguide sets up electric fields in the neighborhood of the two dipoles. These fields induce currents into the dipoles, and the currents cause the dipoles to radiate. By adjusting the length of a dipole of this type, it is possible to change the impedance and consequently the phase of its current and radiation. By suitable choice of lengths and spacing, the radiation from the two dipoles can be made to fall on the main reflector. Various other combinations are used also. More than two dipoles are sometimes seen, and occasionally a combination of two or more dipoles may be used with a splash plate. All of these, however, serve the same purpose, causing the radiation from the waveguide to fall uniformly on the main reflector.

Figure 160. Rear Feed With a Splash Plate.

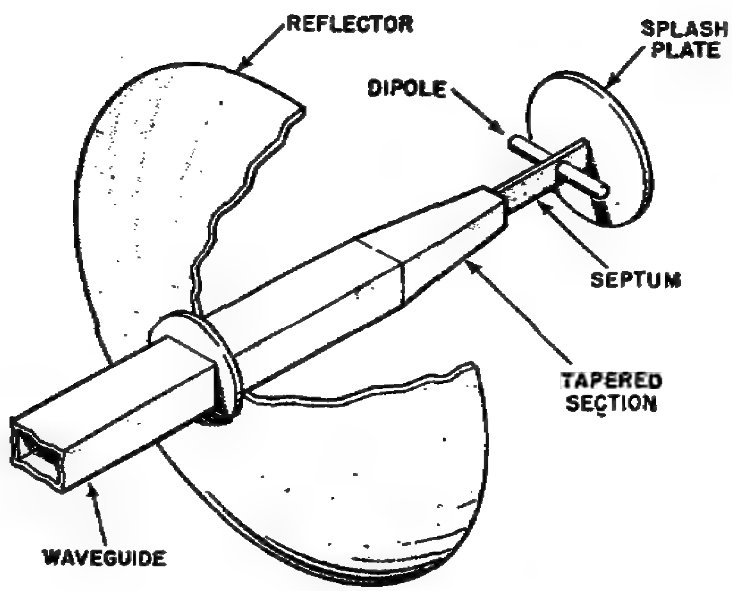
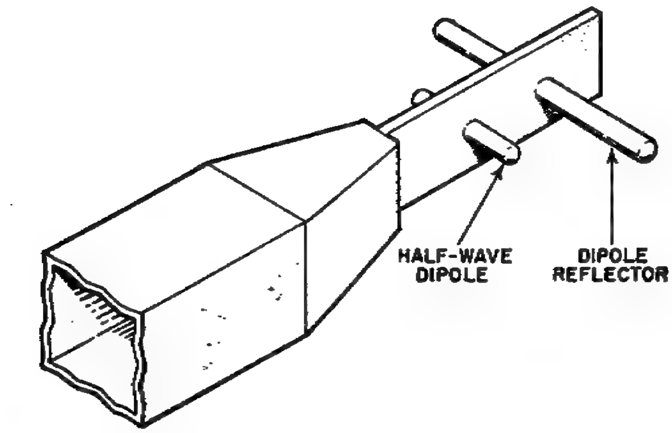
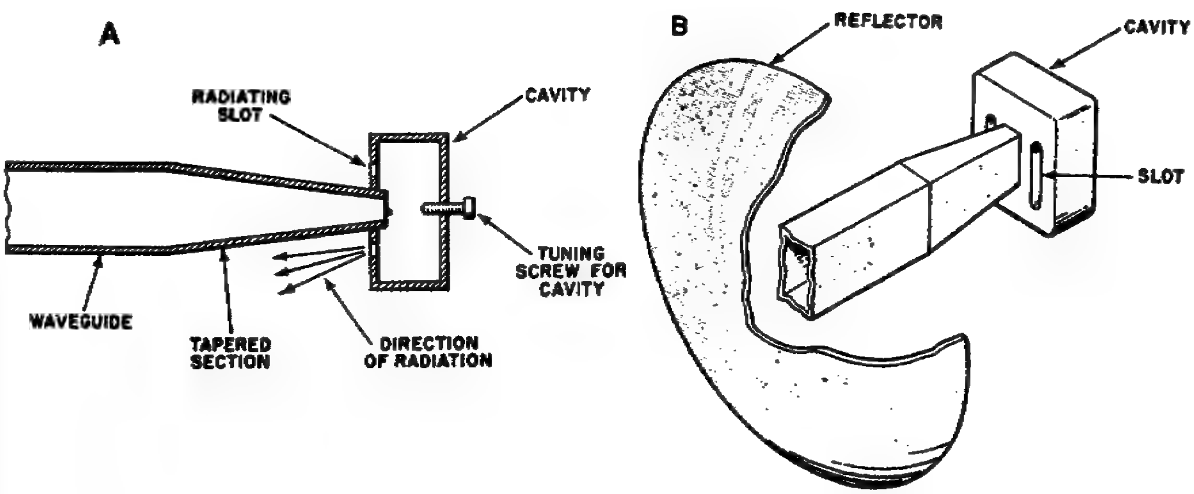


Figure 161. Dipole Reflector.



(2) Cutler feed. Another useful rear feed is the cutler feed shown in Figure 162. This consists of a resonant cavity, which is tuned by means of the adjusting screw, with two radiating slots which feed energy to the reflector. The radiating elements of any of the rear feeds may be enclosed in an airtight box for the purpose of pressurizing the waveguide of coaxial line.

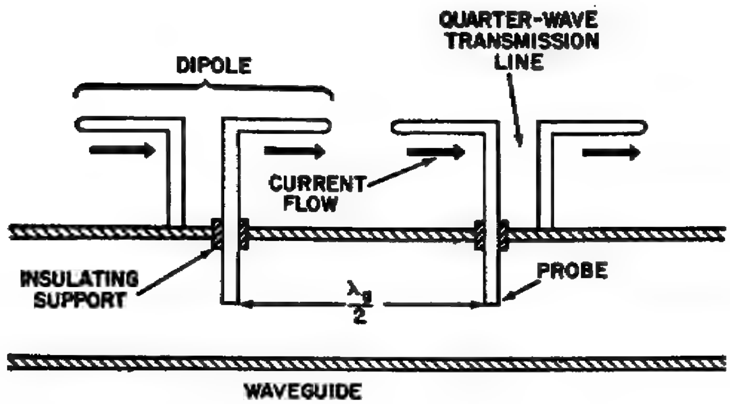
Figure 162. Cutler Feed.



c. Linear array. A linear array is required to feed a parabolic cylinder reflector.

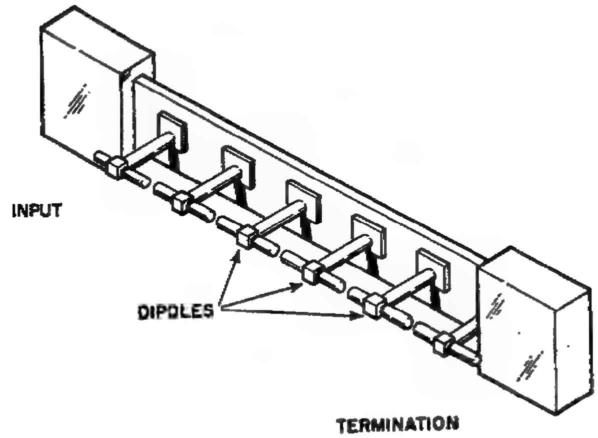
(1) Probe-fed dipoles. The usual array consists of a set of probe-fed dipoles. Each dipole is, in effect, a center-fed, half-wave antenna as shown in Figure 163.

Figure 163. Probe-Fed Dipoles.



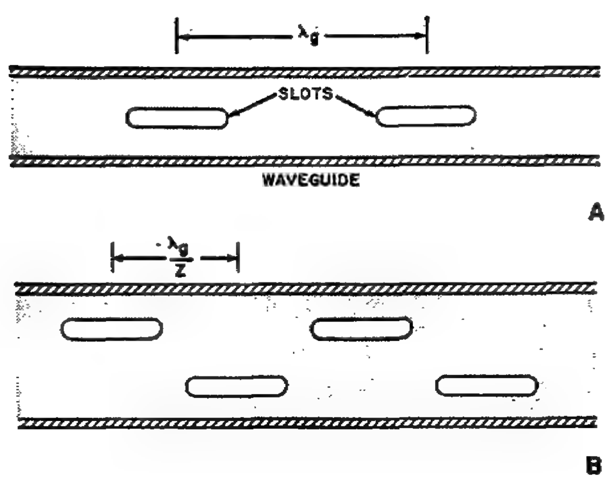
One half of each dipole is fed by the probe, which extends into the waveguide parallel to the electric field. The other half of the dipole is fed by transfer of energy across the quarter-wave, two-wire transmission line which supports the two halves of the dipole. Successive pairs of dipoles are spaced along the waveguide at specific intervals. At the input end of the linear array shown in Figure 164, the energy level in the waveguide is relatively high and the probes extend only a short distance into the waveguide. Near the other end of the array the energy level is lower, because energy has been withdrawn by the earlier dipole probes and the probes extend farther into the waveguide. To avoid any reflection, the waveguide is terminated in its characteristic impedance by a dissipative termination.

Figure 164. Linear Array.



(2) Leaky waveguide. Another type of linear array, which is more rugged but more difficult to design, is made by cutting slots in a waveguide. The slots radiate exactly like the slots in a resonant cavity, and allow energy to leak out of the waveguide. A linear array of this type is called a leaky waveguide. A leaky waveguide is shown in Figure 165. The complexity of the system lies in the difficulty of controlling the amount of radiation from a given slot. In practice, the slots are not as simple as those shown in Figure 165. As with the probe-fed dipole array, the waveguide is terminated in a dissipative termination, the impedance of which matches the characteristic impedance of the waveguide.

Figure 165. Leaky Waveguide.



PRACTICE EXERCISE
(Performance-Oriented)

In each of the following exercises, select the ONE answer that BEST completes the statement or answers the question. Indicate your solution by circling the letter opposite the correct answer in the subcourse booklet.

1. The wavelength of the lowest frequency that can be sent down the waveguide shown in Figure 130 is equal to

   a. the width of the waveguide.

   b. the height of the waveguide.

   c. twice the width of the waveguide.

   d. twice the height of the waveguide.

2. What determines the lowest frequency that a waveguide can handle?

   a. The length of the waveguide.

   b. The A dimension of the waveguide.

   c. The B dimension of the waveguide.

   d. The method of terminating the waveguide.

3. Waveguides and resonant cavities differ in the positioning of the E and H fields and their terminations. The E and H fields in a resonant cavity are

   a. in phase while the E and H fields in a waveguide are 90 degrees out of phase.

   b. 90 degrees out of phase while the E and H fields in a waveguide are in phase.

   c. 90 degrees out of phase while the E and H fields in a waveguide are 180 degrees out of phase.

   d. 180 degrees out of phase while the E and H fields in a waveguide are 90 degrees out of phase.

4. Several methods of coupling are used to transfer energy into, or out of, waveguides. The device that is used to remove samples of energy from a waveguide and transfer these samples to associated test equipment is a

   a. directional coupler.

   b. dummy load.

   c. horn.

   d. loop.

5. If a rotating choke joint is used to couple two sections of waveguide together, the two physical sections appear as one electrical section. Why does the choke joint make the two waveguide sections appear as one electrical section?

   a. The choke joint appears as a half-wave open circuit to the waveguides.

   b. The choke joint appears as a half-wave short circuit to the waveguides.

   c. The choke joint appears as a half-wave open circuit to the waveguides.

   d. The choke joint appears as a quarter-wave short circuit to the waveguides.

6. Twisted sections of waveguide must be at least two wavelengths long to prevent reflections and loss of power. Twisted sections of waveguide are used primarily to

   a. change the polarization of the waves.

   b. connect waveguides to directional couplers.

   c. connect fixed waveguides to rotating waveguides.

   d. match the load impedance to the characteristic impedance of the waveguide.

7. Assume that during the installation of a waveguide, section A and section B are required to be positioned at right angles as shown in Figure 166. The recommended waveguide fitting for this connection is

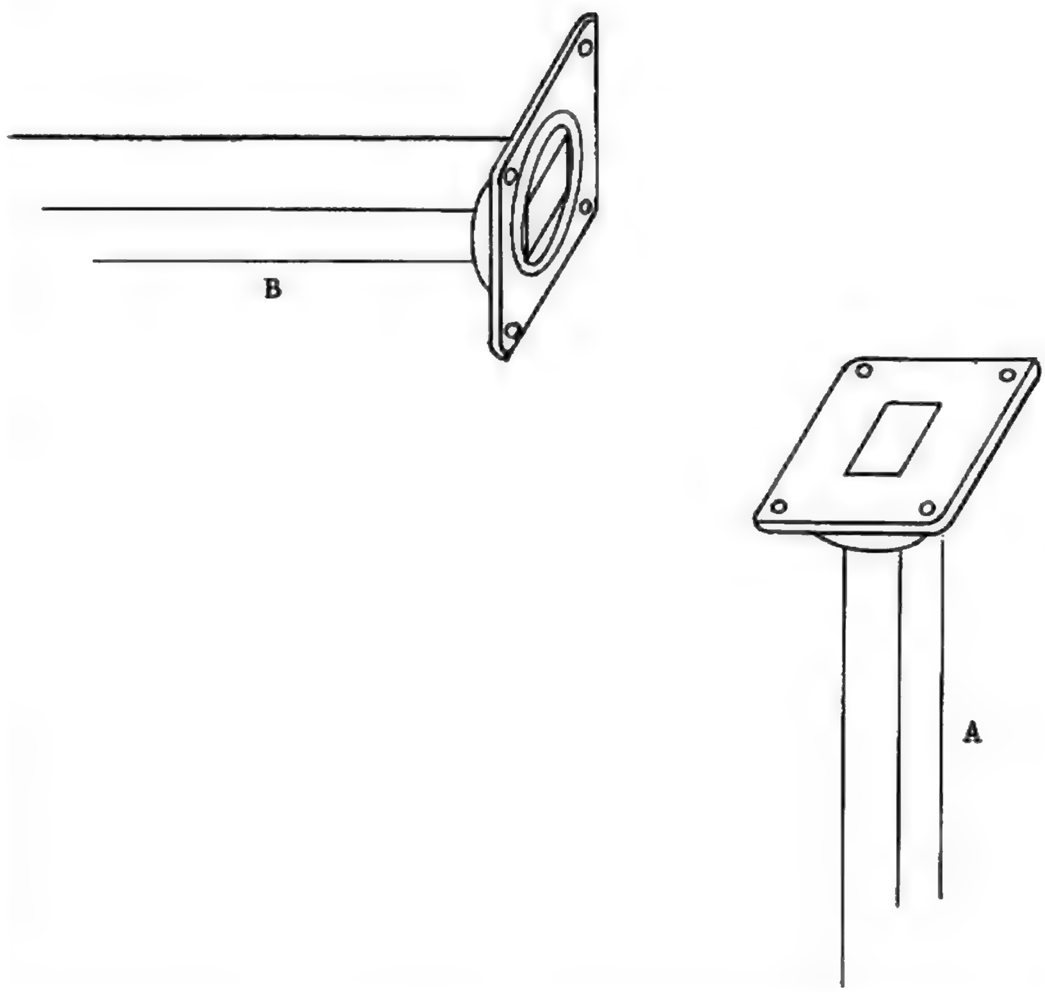
a. a section of flexible waveguide.

b. a mitered H bend.

c. an H bend.

d. an E bend.

Figure 166. Waveguide Fittings.



8. Flexible sections of waveguide are used only when a special type of bend is needed. Flexible sections of waveguide are seldom used because they

   a. have poor insulation.

   b. change the polarization of the wave.

   c. absorb energy in their resistive surfaces.

   d. cause reflections that result in a loss of power.

9. There are several devices used to match the load impedance to the impedance of the waveguide. Some of these devices include the

   a. shutter, slug tuner, and horn.

   b. slug tuner, horn, and window tuner.

   c. window tuner, shutter, and resistive card.

   d. resistive card, window tuner, and slug tuner.

10. When test equipment is used to observe the transmitted pulse spectrum, the power level of the pulse must be reduced to protect the test equipment. The device that will reduce the power without causing reflections in the waveguide is a

    a. resistive card attenuator.

    b. shutter attenuator.

    c. window tuner.

    d. slug tuner.

11. The receiving antenna will absorb maximum energy when the transmitting and receiving antennas are polarized identically. A horizontally polarized antenna is physically positioned

    a. perpendicularly to the earth, and its electric field will be perpendicular to the earth.

    b. perpendicularly to the earth, and its electric field will be parallel to the earth.

    c. parallel to the earth, and its electric field will be perpendicular to the earth.

    d. parallel to the earth, and its electric field will be parallel to the earth.

12. A radar antenna system consists of a feed system and a reflector. The reflector is used to

    a. permit the use of one antenna for both transmitting and receiving.

    b. change the polarization of the transmitted wave.

    c. allow the antenna to radiate in all directions.

    d. make the antenna directional.

13. Assume that the radar antenna shown in Figure 131 has a gain of 2,000. This gain of 2,000 means that the radar antenna

    a. amplifies the RF power 2,000 times.

    b. absorbs 20 percent of the RF power.

    c. absorbs 2,000 times more power than a simple dipole.

    d. radiates 2,000 times more power than a simple dipole.

14. A radar antenna consists of a feed and a reflector. The type of feed that employs a resonant cavity to couple the RF energy to the reflector is a

    a. horn feed system.

    b. dipole feed system.

    c. cutler feed system.

    d. linear array of dipoles.

15. The type of radar beam that will provide accurate azimuth and elevation information is represented in SSTS 52011 in Figure

    a. 154.

    b. 148.

    c. 140 B.

    d. 140 A.

16. The beam pattern shown in Part A of Figure 140 would provide a radar set with accurate

    a. azimuth information.

    b. elevation information.

    c. azimuth and elevation information.

    d. azimuth, elevation, and range information.

17. The type of reflector that would produce the beam pattern shown in Part B of Figure 140 can be described best as a

    a. paraboloid.

    b. metallic lens.

    c. vertically mounted orange peel.

    d. horizontally mounted orange peel.

18. All parabolic cylinders have one thing in common that makes them easy to identify. That is, they are

    a. fed along a focal line rather than at a focal point.

    b. fed at a focal point rather than from a focal line.

    c. all identical in appearance.

    d. all fed from dipoles.

19. The antenna system show in Figure 167 uses a modified parabolic reflector to concentrate the RF energy into the desired beam pattern. The antenna's feed system can be classified as a

   a. rear feed system using a horn.

   b. front feed system using a horn.

   c. rear feed system using a dipole.

   d. front feed system using a dipole.

20. A radar antenna that uses a front feed system is represented in Figure

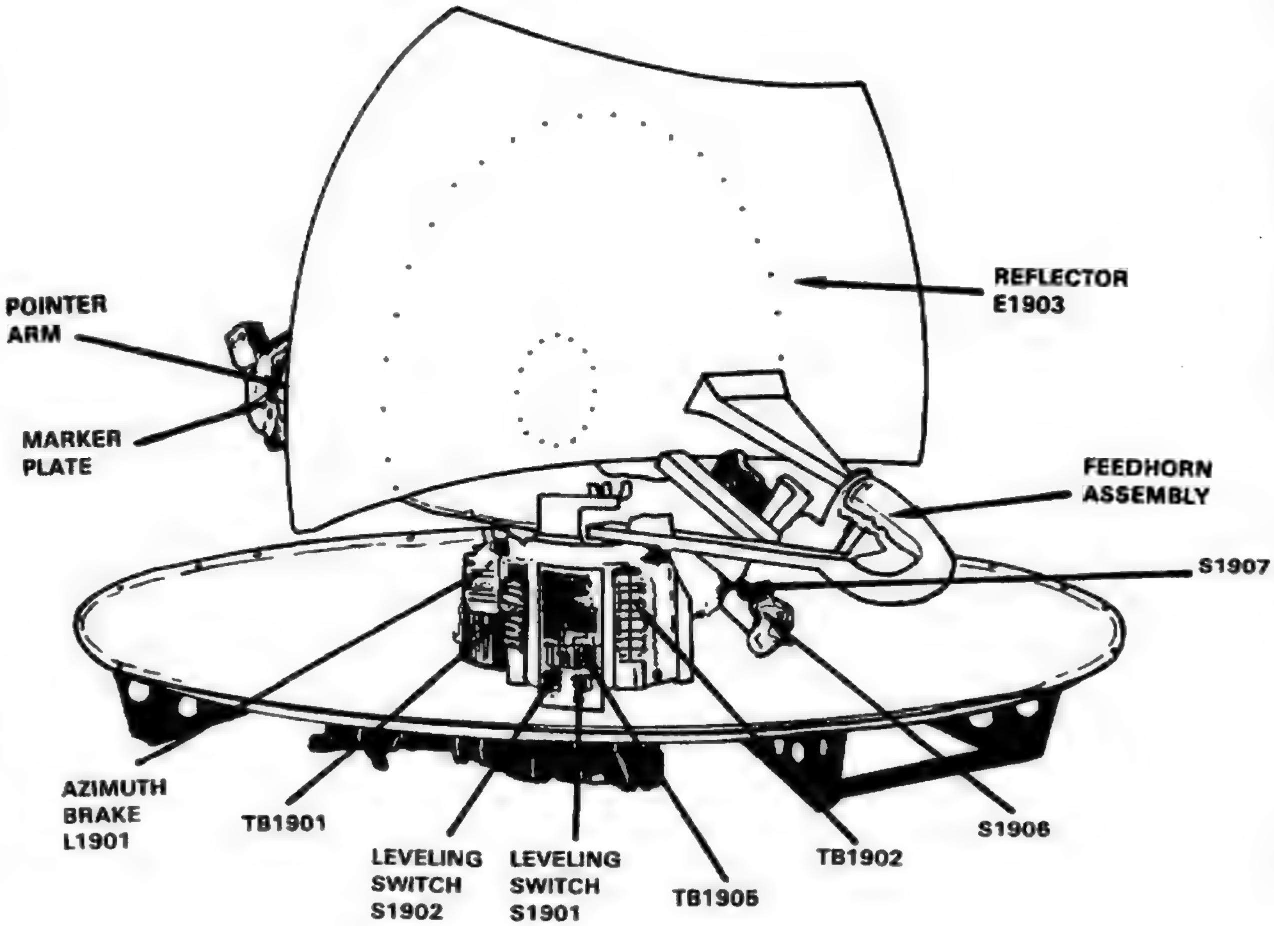
   a. 139 C.

   b. 143.

   c. 149.

   d. 150.

Figure 167. Radar Antenna System.



PRACTICE EXERCISE LESSON SOLUTIONS

AV 5005..............................Radar Transmitters

LESSON 1..................................Transmission Lines

1. b--page 6, para 10d

2. c--page 8, para 12c, pg 7

3. b--page 10, para 15b

4. c--page 10, para 15b

5. c--page 18, SWR Formula

6. c--page 19, para 27b

7. b--page 19, para 27b

8. c--page 22, para 29b, page 28, fig 23

9. a--page 22, para 29a

10. d--page 22, para 29b

A shorted quarter-wave stub will appear as a shorted half-wave stub to the second harmonic. Therefore, the impedance reflected back to the transmission line will resemble the impedance offered by a series-resonant circuit.

11. a--page 29, para 2b, fig 24

12. b--page 30, para 46

$$TD = \text{length} \quad \sqrt{LC}$$

$$\text{length} = TD \div \sqrt{LC}$$

$$\text{length} = (4 \times 10^{-6}-) \quad \div \quad \sqrt{(0.4 \times 10^{-6})\ (10 \times 10^{-12})}$$

$$\text{length} = (4 \times 10^{-6}) \div \sqrt{4 \times 10^{-18}} = (4 \times 10^{-6}) \div (2 \times 10^{-9})$$

$$\text{length} = 2{,}000 \text{ meters}$$

13. a--page 30, para 3b

$Rc = \sqrt{L/C}$

$Rc = \sqrt{(32 \times 10^{-3}) \div (0.2 \times 10^{-6})} = \sqrt{160 \times 10^{3}} = \sqrt{16 \times 10^{4}}$

$Rc = 4 \times 10^{2} = 400$ ohms

14. d--page 37, para 13a

$TD = N \sqrt{LC}$

$TD = 5 \sqrt{(0.3 \times 10^{-3})\ (0.03 \times 10^{-6})} = 5 \sqrt{9 \times 10^{-12}}$

$TD = 5\ (3 \times 10^{-6})$

TD = 15 microseconds

15. d--page 37, para 14d

Charge time $= 2\ TD = 2\ N\sqrt{LC}$

$= 2 \times 4 \sqrt{(1.6 \times 10^{-3})\ (0.4 \times 10^{-6})}$

$= 8 \sqrt{64 \times 10^{-12}}$

$= 8\ (8 \times 10^{-6})$

= 64 microseconds

16. a--page 30, para 3b

$Rc = \sqrt{L/C}$

$Rc = \sqrt{(1.6 \times 10^{-3})\ /\ (0.04 \times 10^{-6})}$

$Rc = \sqrt{40 \times 10^{3}}$ Rc = 200 ohms

17. a--page 37, para 13a, page 34, fig 27

Charge time $= 2\ TD = 2\ N \sqrt{LC}$

Charge time $= 2 \times 3 \sqrt{(100 \times 10^{-6})\ (.01 \times 10^{-6})} = 6 \sqrt{1 \times 10^{-12}}$

Charge time = 6 microseconds

$Rc = \sqrt{L/C}$

$Rc = \sqrt{(100 \times 10^{-6}) \div (.01 \times 10^{-6})} = \sqrt{10,000}$

Rc = 100 ohms

The charging resistance and the characteristic resistance of the circuit are equal and the ATL will be fully charged after 6 microseconds. Therefore, 6 microseconds after the voltage is applied, the voltage across the charging resistance will be equal to zero.

18. c--page 38, para 15d

The pulse has a time duration of two TDs. Therefore, the circuit will have an applied voltage equal to twice the amplitude of the output pulse (2 x 100 = 200 volts).

19. d--page 42, para 18a, fig 34

20. d--page 43, para 18c, d

LESSON 2...............................High-Level Modulation

1. c--page 68, para 6

2. c--page 71, para 2b

3. b--page 71, para 2b

4. a--page 74, para 2a

5. a--page 77, para 3c

6. b--page 81, para 2c

7. d--pages 81, 82, para 3b

8. b--page 83, para 2

9. c--page 66, para 2

When a pulse-forming network's characteristic resistance is equal to its load resistance, the output pulse's amplitude will be equal to one-half the charge across the PFN. The PFN charges to twice the input voltage.

Amplitude = 30 kv/2 = 15 kv

The pulse width will be equal to two TDs.

Pulse width = 2 x 0.75 usec = 1.5 microseconds

10. d--page 73, para 1

11. c--pages 73, 76, para 3a

12. a--pages 83, 84

13. d--page 86

14. a--page 86

15. b--page 76

16. c--page 77

17. a--page 77

18. b--page 78

19. d--page 86

20. b--page 64

LESSON 3..................................Resonant Cavities and Magnetrons

1. c--page 104

2. d--page 104

3. c--page 110, para 14d

4. b--page 110, para 14b

5. a--page 110, fig 77

6. b--page 112, para 17

7. d--page 113, para 21a

a. Minimum output is obtained by placing a coupling loop at point A and parallel to the magnetic field.

b. Minimum output obtained by placing the coupling loop at point B because the magnetic field is minimum.

c. The magnetic field is not at its maximum strength at point C; therefore, maximum output is not obtained.

d. Maximum output is obtained by placing the coupling loop at point D and placing it perpendicular to the magnetic field.

8. d--page 113, para 20c

9. a--page 115, para 22b

10. b--page 118, fig 82

11. c--pages 122, 123, fig 85

12. a--page 122, para e

13. a--page 127, para 11c

14. d--page 130, para 14, fig 91

15. b--page 133, para 17a

16. c--page 133, para 17a

17. c--page 135, para 19

18. a--page 134, para 18a

19. c--page 137, para a

20. a--page 141, para 29a(3)

LESSON 4.................................Antennas and Waveguides

1. c--page 163, para 7d

2. c--page 163, para 7d

3. b--page 164, para 10c

4. a--page 171, para 18

5. b--page 173, para 21c

6. a--page 176, para 25b

7. d--page 176, para 24, fig 122

8. d--page 177, para 26a

9. b--page 172, para 20b, page 180, para d

10. a--page 181, para 31a

11. d--page 187, para 66

12. d--page 199, para 20

13. c--page 192, para 11d

14. c--page 195, para 14d

15. a--page 211, para 32

16. b--page 197, para 18a

17. d--page 203, para 25

18. a--page 207, para 29

19. b--page 213, para (1), fig 155

20. c--page 205